VOL.107 NO.TE3. MAY 1981

TRANSPORTATION ENGINEERING JOURNAL OF ASCE

PROCEEDINGS OF
THE AMERICAN SOCIETY
OF CIVIL ENGINEERS

AEROSPACE
AIR TRANSPORT
HIGHWAY
PIPELINE
URBAN TRANSPORTATION

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ISSN 0569-7891

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This Journal is published bimonthly by the American Society of Civil Engineers. Publications office is at 345 East 47th Street, New York, N.Y. 10017. Address all ASCE correspondence to the Editorial and General Offices at 345 East 47th Street, New York, N.Y. 10017. Allow six weeks for change of address to become effective. Subscription price to members is $12.50. Nonmember subscriptions available; prices obtainable on request. Second-class postage paid at New York, N.Y. and at additional mailing offices. TE.

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Sulfur: Potential Pavement Binder of the Future, by Gerald D. Love (Sept., 1979. Prior Discussions: July, Nov., 1980).
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INFORMATION RETRIEVAL

The key words, abstract, and reference "cards" for each article in this Journal represent part of the ASCE participation in the EJC information retrieval plan. The retrieval data are placed herein so that each can be cut out, placed on a 3 × 5 card and given an accession number for the user's file. The accession number is then entered on key word cards so that the user can subsequently match key words to choose the articles he wishes. Details of this program were given in an August, 1962 article in CIVIL ENGINEERING, reprints of which are available on request to ASCE headquarters.

16232 ACCIDENT INVESTIGATOR BIAS POTENTIAL

KEY WORDS: **Accident investigation; Accident investigation training;** Accident reconstruction; **Behavior research;** Engineering education; Engineering psychology; Judgment; Observation; **Traffic accidents**

ABSTRACT: Recent and on-going behavioral research suggests a potential for bias on the part of the accident investigator who relies on personal subjective judgment rather than thorough objective analysis. Experience suggests that such bias has the greatest potential for producing accident reconstruction errors; these errors reflect an expected low self-testing investigator behavioral predisposition, one that tends to augment damage, danger and threat. The most obvious ameliorative solution to this problem is extensive objective analysis training (in engineering and basic science) for accident investigators. However, because even engineers exhibit behavioral biases in traffic engineering decisions, such training must be coupled with expressive awareness training.

REFERENCE: Hutchinson, John W., Roberts, John M., and Scorsone, Francesco G., "Accident Investigator Bias Potential," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16232**, May, 1981, pp. 255-262

16244 SAVINGS AND PREFERENTIAL TREATMENT PROJECTS

KEY WORDS: Car pools; **Energy conservation; Energy consumption; Highway transportation;** Highway usage; Petroleum; Time spent driving; **Transportation studies;** Urban highways; **Urban transportation;** Vehicle operating costs

ABSTRACT: More than half the U.S. petroleum supply is used for transportation, and highway transportation use can be cut substantially. This can be accomplished through the use of high occupancy vehicles—particularly carpools, vanpools and buses. A major incentive for high occupancy vehicles is preferential treatment projects that provide significant time saving. A concerted effort is needed to develop preferential treatment projects and the associated policies which will complement the physical improvements. A major Federal program is recommended that would develop physically separate preferential treatment projects in urban radial corridors. Policies to encourage ride-sharing and discourage single occupant vehicles are also recommended. Energy savings of up to 10 percent of total highway usage could be achieved nationwide.

REFERENCE: Rothenberg, Morris J., "Energy Savings Potential of Preferential Treatment Projects," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16244**, May, 1981, pp. 263-271

16252 TRANSIT OPERATING STRATEGIES

KEY WORDS: Dispatching systems; **Emergencies; Emergency services;** Entrainment; Guidelines; **Operation and maintenance; Transit systems; Transportation management; Transportation planning**

ABSTRACT: Transit operating strategies (TOS) are designed to address a set of problems arising from a sudden shock to the normal steady state operation of a transit system. The identification and classification of sets of transit operating strategies, the constraints and environment under which a transit operating strategy is implemented, and the class of problems that each TOS can best address are explored. Heuristic implementation guidelines for each identified transit operating strategy are developed, intending to improve the search process in devising control responses. No attempt is made to optimize the operation of a transit system under non steady-state conditions. Rather, the implementation guidelines serve to search and subsequently implement good control responses.

REFERENCE: Spiller, David, "Transit Operating Strategies: Tentative Guidelines," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16252**, May, 1981, pp. 273-285

16248 WHAT TO DO ABOUT URBAN GOODS MOVEMENT?

KEY WORDS: **Freight transportation; Transportation management;** Transportation planning; **Transportation systems; Urban planning;** Urban traffic flow; **Urban transportation**

ABSTRACT: Although a significant body of information regarding urban goods movements has evolved over the past ten years, there is still much to be accomplished if the announced intention of the Secretary of Transportation—that all regional transportation planning must address urban goods movements—is to be realized. Research in the early 1970s outlined problems and potential solutions which have been substantially verified in more recent studies, but still no systematic planning approach exists. Transportation systems management (TSM) has been promoted since 1975 and has become a component of the urban transportation planning (UTP) process. However, urban goods movement, as a part of local TSM actions, has only received limited consideration and study. After a review of these developments, the issue of integrating urban goods movement into TSM planning of activities is addressed, and certain probable developments of the 1980s, which will further enhance the importance of urban goods movement, are examined.

REFERENCE: Diewald, Walter J., "TSM: What to do About Urban Goods Movement?," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16248**, May, 1981, pp. 287-299

16246 POLAR ORTHOTROPIC CIRCULAR PLATES

KEY WORDS: **Aerospace engineering;** Asymmetry; **Bending;** Displacement; Finite element method; Fourier series; Mathematical models; **Orthotropic plate; Plates;** Stiffness; **Structural analysis**

ABSTRACT: The asymmetric bending of polar orthotropic circular plates using the finite element method is explored. The plate bending model consists of one-dimensional circular and annular ring segments using a Fourier series approach to model the problem asymmetries. Using displacement functions, which are the exact solutions of the plate bending equation, the stiffness coefficients corresponding to the 0th, 1st, and nth harmonics are presented in closed form. These stiffness coefficients, which can be readily coded into any special or general purpose structural analysis computer program, represent the exact solution to any structural model consisting of nodal displacements and forces. An example is considered which compares the mathematical formulation using this technique to the classical solution.

REFERENCE: Pardoen, Gerard C., and Barton, David E., "Asymmetric Bending of Polar Orthotropic Circular Plates," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16246**, May, 1981, pp. 301-316

16230 REMOTE SENSING FOR POWER PLANT SITING

KEY WORDS: **Aerial photography; Aerial surveys;** Nuclear electric power generation; **Nuclear power plants; Power plant location; Radar;** Remotely sensed data; **Remote sensing; Site selection;** Site selection studies; Site surveys

ABSTRACT: Remote sensing techniques enhance the selection and evaluation process for nuclear power plant siting. The principal advantage is the synoptic view which improves recognition of linear features, possibly indicative of faults. The interpretation of such images, in conjunction with seismological studies, also permits delineation of seismo-tectonic provinces. In volcanic terrains, geomorphic-age boundaries can be delineated and volcanic centers identified, providing necessary guidance for field sampling and regional model derivation. The use of such techniques is considered for studies in the Philippines, Mexico, and Greece.

REFERENCE: Siegal, Barry S., and Welby, Charles W., "Remote Sensing for Nuclear Power Plant Siting," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16230**, May, 1981, pp. 317-329

16269 URBAN GROWTH AND TRANSPORTATION ENERGY

KEY WORDS: Central business districts; Central city; **Cities;** Computer models; Employment; **Energy consumption;** Growth rate; **Passenger transportation;** Residential density; **Urban areas; Urban development; Urban transportation**

ABSTRACT: An aggregate digital computer simulation model was used to test the urban passenger transportation energy consumption associated with different patterns of nuclear growth in a hypothetical city. The model simulated the effects of various central and noncentral locations for residential, employment, and retail growth clusters. Centralized urban growth is more efficient, in terms of transportation energy consumption, than noncentralized growth. Off-center manufacturing employment clusters are the least energy efficient of non-centralized cluster, and clusters at the edge of the established urban area are less attractive for all land use types. The implications for near term urban decision making are explored.

REFERENCE: Schofer, Joseph L., Weisel, William, and Peskin, Robert L., "Nucleated Urban Growth Effects on Transportation Energy Consumption," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16269,** May, 1981, pp. 331-344

16276 FLY ASH SULFUR CONCRETE

KEY WORDS: **Concrete; Construction materials; Fly ash;** Materials engineering; Materials tests; **Pavement bases;** Pollution; **Sulfur; Waste usage**

ABSTRACT: Two "waste" products, fly ash and elemental sulfur, can be combined with a modifying agent to produce a potentially useful construction material, fly ash sulfur concrete (FASC). Production of the material in the laboratory is simple and direct. Strength characteristics of FASC are affected by the amounts of the ingredients present and the unit weight of the mixture. Compared with a conventional crushed stone aggregate, FASC is a viable highway pavement base course material with respect to predicted theoretical pavement performance. Definitive assessments of the utility of FASC await reliable cost and durability data and construction experience. From perspectives of both environmental protection and energy conservation, waste products (either singly or in combination with other wastes or stabilizing agents, or both) can and should be considered as candidate construction materials.

REFERENCE: Head, William J., and Liao, Min-Fu, "Fly Ash Sulfur Concrete," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16276,** May, 1981, pp. 345-363

16274 TAPS DESIGN CONCEPTS: ENVIRONMENTAL CONCERNS

KEY WORDS: **Arctic engineering;** Arctic regions; Cost effectiveness; **Design concepts; Environmental engineering;** Environmental factors; Geotechnical engineering; **Natural resources;** Permafrost; **Pipelines; Structural design**

ABSTRACT: The engineering concepts utilized in the design, construction, and operation of the Trans-Alaska Pipeline System (TAPS) were often new and in many cases state-of-the-art. In order to accommodate the concerns for constructing and operating a hot oil pipeline in permafrost soil, unique features were engineered into TAPS. These design concepts included accommodating for thaw-unstable soils, earthquakes, and major river. Additionally, the system includes a sophisticated leak detection and internal pipeline monitoring system as part of the overall pipeline monitoring operations. While many factors of TAPS are new concepts to crude oil pipelines, the advancement of pipeline designs has materially increased as has the industry's ability to accommodate the environmental concerns associated with pipelines in seasonal and permafrost areas.

REFERENCE: Turner, Morris J., "TAPS Design Concepts: Environmental Concerns," *Transportation Engineering Journal,* ASCE, Vol. 107, No. TE3, **Proc. Paper 16274,** May, 1981, pp. 365-380

U.S. Customary-SI Conversion Factors

In accordance with the October, 1970 action of the ASCE Board of Direction, which stated that all publications of the Society should list all measurements in both U.S. Customary and SI (International System) units, the following list contains conversion factors to enable readers to compute the SI unit values of measurements. A complete guide to the SI system and its use has been published by the American Society for Testing and Materials. Copies of this publication (ASTM E-380) can be purchased from ASCE at a price of $3.00 each; orders must be prepaid.

All authors of *Journal* papers are being asked to prepare their papers in this dual-unit format. To provide preliminary assistance to authors, the following list of conversion factors and guides are recommended by the ASCE Committee on Metrication.

To convert	To	Multiply by
inches (in.)	millimeters (mm)	25.4
feet (ft)	meters (m)	0.305
yards (yd)	meters (m)	0.914
miles (miles)	kilometers (km)	1.61
square inches (sq in.)	square millimeters (mm^2)	645
square feet (sq ft)	square meters (m^2)	0.093
square yards (sq yd)	square meters (m^2)	0.836
square miles (sq miles)	square kilometers (km^2)	2.59
acres (acre)	hectares (ha)	0.405
cubic inches (cu in.)	cubic millimeters (mm^3)	16,400
cubic feet (cu ft)	cubic meters (m^3)	0.028
cubic yards (cu yd)	cubic meters (m^3)	0.765
pounds (lb) mass	kilograms (kg)	0.453
tons (ton) mass	kilograms (kg)	907
pound force (lbf)	newtons (N)	4.45
kilogram force (kgf)	newtons (N)	9.81
pounds per square foot (psf)	pascals (Pa)	47.9
pounds per square inch (psi)	kilopascals (kPa)	6.89
U.S. gallons (gal)	liters (L)	3.79
acre-feet (acre-ft)	cubic meters (m^3)	1,233

ACCIDENT INVESTIGATOR BIAS POTENTIAL

By John W. Hutchinson,[1] John M. Roberts,[2] and Francesco G. Scorsone[3]

(Reviewed by the Highway Division)

INTRODUCTION

The behavioral predispositions of accident investigators seem to offer the potential of adversely affecting the outcome of accident investigations. When selected findings from behavioral research are compared with the types of mistakes made by traffic accident investigators, there appear to be parallels worthy of attention. The potential for bias needs to be carefully researched with a view toward development of investigator training to avoid predictable errors in accident reconstruction.

Although some examples of possible accident reconstruction biases are presented, there is no intent to say they are already proven nor to imply that their basis in accident investigator behavioral predisposition is a known fact. The intent is to present findings from behavioral research which clearly suggest that part of the potential or real investigator error problem in accident reconstruction may have an investigator behavioral basis. The prospect that it does is sufficiently compelling to warrant some caution on the part of accident investigators and attract the attention of researchers. As a minimum, familiarity with the proposed concept will at least be beneficial from the standpoint of the parallels drawn with the driver behavioral factors involved.

DRIVER BEHAVIOR RESEARCH

Driver behavior research based on power styles from game studies has shown a directional tendency for the general population to be roughly divided between two attitudinal poles of motivational predisposition, low self-testing at the one extreme and high self-testing at the other (12,13). The high and low self-testing

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on October 31, 1979. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0255/$01.00.

labels are derived essentially from the idea of "high" need for stimulation and "low" need for stimulation as reflected in the choices and attitudes of different players. In certain activity situations, low self-testing is associated with caution which appears to be derived from judgemental accentuation while high self-testers tend toward daring or risk-taking on the basis of learned or assumed limits.

Studies now in progress show that high self-testers are also high on the Vando scale (20–22) indicating that they are, according to the analysis by Loy and his associates (9,10), high on a need for stimulation scale. Correspondingly, low self-testers manifest a low need for stimulation as evidenced by their score on the Vando scale. Other research suggests that the high self-testers are also reducers in the sense that they have high pain tolerances and are able to reduce incoming stimuli, whereas low self-testers are precisely the opposite. They have low tolerances for pain stimuli and tend to augment incoming signals. Other research in progress will explore these relationships in greater detail. For the present we can only suggest that these relationships probably exist.

High and low self-testing attitudes have been shown to be associated with significant differences in: (1) Judgement of danger or threat represented by filmed driving errors (4); (2) speed and lane placement on a curve under various environmental conditions (14); (3) judgement of the extent of damage to accident involved vehicles portrayed in a scaled set of photographs (15); (4) choice of pilot assignments with various degrees of associated risk (15); (5) frequency of traffic accident involvement (16); (6) traffic control preferences of traffic engineers (17); and (7) vehicle choice (14,18).

In general, low self-testers tend to: (1) Augment and avoid damage, danger, and threats; (2) drive at lower speeds; and (3) have fewer traffic accidents than high self-testers. High self-testers tend to be better at judging damage, danger or threat because they are more inclined toward choices and habits involving exposure to risks which provide opportunities for experience in such matters. However, high self-testers also tend to reduce the realities of damage, danger or threat, in that they tend to accept less compelling reasons for taking risks and are more frequently involved in traffic accidents. Such differences in the attitudes of high and low self-testers appear to be exhibited most prominently under conditions of mild stress (14).

There is no reason not to expect to find these same attitudinal differences reflected in the practice of accident investigation wherever personal judgements rather than disciplined objective analyses are involved in decision making.

Accident Investigation

Limited research suggests that personal judgements on the part of accident investigators from police agencies, adjusting companies, and Federal agencies (BMCS, NTSB, ICC, NHTSA, etc.) should reflect attitudes that are more low self-testing (augmenting) than would be expected from the general population because those interested enough in safety to make it a career or employment choice have been found lower on the self-testing scale (15). Furthermore, the funding of safety research, promotion of safety features, and enforcement of safety laws all have a primary impetus that is low self-testing because safety sells best to those who tend to augment the damage, danger or threat from

lack of safety. As a minimum then, success in the safety milieu is enchanced by training and/or discipline along low self-testing lines.

Allied with the possible adverse effects of accident investigator motivational predisposition is the tendency of all involved agencies (police, insurance, courts, researchers) to rely too heavily upon eye witnesses; this in spite of the clear warning from Loftus (19) and others (1) that the mind can elaborate and fabricate truthfully. A low self-testing witness can truthfully augment the damage, danger or threat of any aspect of a traffic accident; a high self-testing witness can truthfully reduce or diminish the significance of accident factors based on personal behavioral predisposition and the input inferences from the way an accident investigator's questions are *worded*.

The interplay of motivational profiles of witnesses and interviewers should be expected to either reinforce or inhibit the exposition of many relevent "facts" in the minds of the parties to and witnesses of traffic accidents. For example, a low self-testing police officer, unaware of the energy dissipation significance of 12 to 13 inches of crush (2) on one fender of a teenager's car, might ask, "how fast were you going, anyhow?" If there is a truthful reply anywhere in the range from 5 to 15 miles per hour, the investigating officer may respond "well, I can tell you were going a lot faster than that," and all subsequent information from this interview is not only discounted by the officer but influenced by his reaction. There is even a court case (see Writ of certiorari to Dade County Florida Circuit Court, quashing the order of Judge George Orr, 3rd District Court of Appeals, July 1977, Case #77-1100, Patrick Moore, et. al. versus Huntington National Bank, et. al.) in which a judge personally reprimanded (and barred the testimony of) a highly qualified accident reconstruction expert witness for assigning a similar vehicle speed (5 mph to 15 mph) to a car with similar crush (12 in. to 13 in.) because the judge could not believe that such a small change in velocity at impact could be accompanied by sufficient occupant head acceleration to "pop the eyeballs of the driver right out of her head" as claimed in other testimony.

Judges, jurors, witnesses, drivers, and accident investigators should be expected to occasionally succumb to their own personal set of prejudices, beliefs and misconceptions derived from years of experience in exercising a high or low self-testing attitude. The occasions for errors resulting from such motivational predispositions would appear to be enhanced by lack of understanding of the significance of available physical evidence and consequential reliance upon personal judgment.

Investigator Error

Judgmental errors by accident investigators appear to be frequently associated with factors suggesting that the attitudes of police investigators are more low self-testing than the attitudes of the general population. This is not unexpected in view of essential police discipline and training to look for drunk drivers, speeders, and other diagnostic symptoms of danger or threat on the highway. In cases with incontrovertible physical evidence to the contrary, fault in accident causation appears to be most often erroneously assigned to: (1) The driver engaged in a maneuver enjoyed by high self-testers and not enjoyed by low self-testers such as overtaking and passing; (2) the driver of the larger and

therefore most threatening vehicle; (3) the driver of the vehicle inflicting the most damage or injury to others; (4) the surviving, least injured or uninjured driver; (5) the driver of the vehicle suffering the least damage; (6) the driver of the vehicle on the inside of the curve on two-lane, two-way roads [low self-testers on the outside of the curve tend to shy to the outside (14)]; (7) the driver of the vehicle in a single vehicle accident, especially if it is a sporty vehicle. Several of these erroneous bases for driver fault assignment seem to be present in cases involving the most grossly incompetent accident reconstruction efforts by police investigators, e.g., point of impact missed by several hundred feet or speed overestimated by 50% to 100%.

Twenty-four traffic accident cases involving reconstruction errors were recently examined in depth. In three of these cases, no driver fault assignments were made by police investigators. In the remaining 21 cases, fault was assigned to the wrong driver. Two or more of the above suggested low self-tester biasing factors were present in each of these 21 cases. The table summarizes the frequency of occurrence of each factor in relation to driver fault in accident causation. It is interesting, if not frightening, to note that these potentially biasing factors were not related to wrongly accused drivers in only three of 85 occurrences.

There is no intent to imply that high self-testing attitudes on the part of accident investigators do not occasionally generate accident reconstruction errors in the opposite direction. However, there is directional evidence from the authors' experience that failure to recognize and/or understand physical evidence at the scene of an accident is more conducive to low self-testing judgemental error. This probably derives partially from low self-testing motivational predisposition, partially from investigator training and discipline along low self-testing lines, and largely from inadequate training in recognition and objective analysis of physical evidence, conjoined with inadequate time and resources, especially if the investigator is a police officer.

Possible Solutions

Ameliorative solutions to the problem of adverse behavioral effects upon the outcome of accident investigations might consist of: (1) Providing police officers, insurance adjusters, and other producers and users of accident data with an expressive awareness that will allow recognition of the potential for bias in themselves and others; (2) decreasing the opportunity for judgemental bias through better training and discipline in all areas or objective analysis required for competent accident reconstruction (2,3,5,6,8,11); and (3) as suggested by many police administrators, establishment of a well-trained and disciplined cadre of paraprofessional accident reconstruction specialists to serve the police, the insurance industry, the courts and other producers and users of accident data in somewhat the same way that paramedics serve the medical profession.

Efforts along this line in the United States have been led by the National Highway Traffic Safety Administration (NHTSA). In the recently concluded data gathering process for the National Crash Severity Study (NCSS), behavioral biases in accident reconstruction were probably largely controlled through computer aided accident reconstruction requirements and the utilization of a private quality control contractor.

Such NHTSA efforts to establish a reliable National Accident Sampling System

(NASS) are certainly needed. However, the individual accident involved members of the society being served by such efforts are understandably less concerned with the statistical significance and reliability of national samples than they are with biases and errors in the police and insurance adjusters reports used against them in court or as a basis for raised insurance premiums, or both. An equally commendable ongoing NHTSA effort is therefore attention to the day to day needs of society through the multidisciplinary highway collison investigation training made available to police officers.

Many American universities and institutes also have accident reconstruction training courses which can be predicted to lessen the adverse behavioral effects

TABLE 1.—Potential Bias Factor Frequency in 21 Cases[a]

Factor (1)	Related to innocent driver (wrongly accused) (2)	Related to other driver(s) (not accused) (3)
High self-testing maneuver	10	0
Larger vehicle[bc]	12	2
Most damage inflicted by vehicle[b] of this driver	11	1
Surviving, least injured, or uninjured driver[b]	14	0
Least damaged vehicle[b]	12	0
Driver on inside of curve (right-hand curve following)	9	0
Single vehicle accident	5	0[d]
High self-testing or sporty vehicle[c]	9	0
Total	82	3

[a]This table *does not* purport to indicate frequency of police error in reconstructing accidents; it suggests only that these potentially biasing factors may be very frequently related to wrongly accused drivers *when* errors in assignment of driver fault in accident causation are made by police investigators.

[b]Frequently, but not always, *all* present in truck versus car accidents.

[c]Seldom pertain to the same driver. They did in only two of these 21 cases.

[d]The zero is appropriate; single vehicle accidents are frequently precipitated by actions of other drivers. For example, a school bus driver stopping to discharge a child on a blind curve in a "no passing" zone at the bottom of a steep grade without displaying school bus warning systems when a heavily laden truck runs over the child, but the truck is the "single vehicle" involved in collision.

of personal judgement by strengthening investigator reliance upon disciplined objective analysis. The missing ingredient in the curricula of almost all such training efforts known to the authors is a simple, quick-and-dirty, easily understood and useable explanation of accident investigator behavioral predispositions that offer the potential for bias. NASS team members cannot be expected to function with peak efficiency under the handicap of such a lack of awareness because they will be dealing with police reports in much the same manner as required of NCSS teams.

Professional and paraprofessional accident reconstruction cadres in the service

of police agencies also need an expressive awareness that will allow recognition of the potential for bias in themselves and the even greater potential for bias in officers who have not shared in their specialized advanced accident reconstruction training.

The greatest need for such an awareness obviously lies at the level of those required to prepare traffic accident reports on a routine basis who are normally engaged in the performance of myriad other essential duties of the average street officer. The routine police report is the point of beginning from which the wrongly accused driver can often look forward to seeking redress in an already overburdened and underfinanced court system, sometimes with the prospect of spending life savings or years of future earnings, or both, in defense against civil or criminal charges while the "statute of limitations" on public and private interest runs out for the driver(s) actually at fault in accident causation.

It can be argued with some credence that advanced accident reconstruction training such as that provided by the Arizona Law Enforcement Officers Advisory Council cannot and should not be provided for every officer required to prepare traffic accident reports. However, the same logic demands an expressive awareness and the part of every officer not provided with such objective analysis training that decreases the potential for bias.

The time and level of training required to grasp the essential features of the self-testing phenomenon are not comparable to requirements in understanding the Minnesota Multiphasic Personality Inventory, the Vando Scale or vehicle dynamics specialists' mathematical models. The basic concept of self-testing and its applications are very simple and quite readily adapted to personal verification by simple everyday observations from either end of the self-testing scale.

The concept, in fact, is so simple that at least one of the impediments to needed funding for this research has probably been the tendency of potential funding agencies to jump to the erroneous conclusion that the self-testing phenomenon is already sufficiently defined by the events it is supposed to explain, i.e., too practical to lend itself to basic research and too basic to be applied research. However, experience suggests that continuing to ignore this phenomenon at work in accident reconstruction may simply be too frightening (see Table 1).

Conclusions

Recent and on-going behavioral research suggests a potential for bias on the part of the accident investigator who relies on personal subjective judgement rather than thorough objective analysis based on properly interpreted physical facts. Experience suggests that such bias has the greatest potential for producing accident reconstruction errors reflecting an expected low self-testing investigator behavioral predisposition, one that tends to augment damage, danger and threat. The most obvious ameliorative solution to this problem is extensive objective analysis (engineering and basic science) training for accident investigators. However, because of the fact that even engineers have been shown to exhibit behavioral biases in traffic engineering decisions, it is suggested that such training must be coupled with expressive awareness training. Since the basic concept of expressive self-testing and its applications are very simple and quite readily

adapted to personal verification through simple everyday observations by persons on either end of the self-testing scale, it is recommended for this purpose.

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ENERGY SAVINGS POTENTIAL OF PREFERENTIAL TREATMENT PROJECTS[a]

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(Reviewed by the Urban Transportation Division)

The statistics related to transportation's consumption of energy products are, by now, well known to the transportation profession as well as the general public. Transportation accounts for 25% of U.S. energy consumption and over half of the petroleum supply. By far the biggest transportation user of petroleum products is the passenger car as shown on Table 1.

The statistics are very revealing and point out the options that policy makers are faced with when they try to reduce our consumption of oil. Although nonhighway modes use large quantities of fuel, there is little flexibility in reducing their usage. Obviously some airline flights can be discontinued and some trains can be cancelled but in each of these cases there is a substantial reduction in the service provided if significant savings are to be achieved.

It is the highway mode that attracts the conservationist's attention. With the average automobile capable of carrying between four and six persons, but usually carrying only one, we have a system that is operating at less than 25% of its seated capacity. Airlines and trains would go out of business if they could only maintain those occupancies. Perhaps it is time that we apply similar standards to our highway system that private business apply to their services.

In actuality this application of load factors has already begun. In the last several years the promotion of ride-sharing has become a national priority. In association with ride-sharing has been the development of preferential treatment facilities for high occupancy vehicles (HOV's) which allow buses, vanpools, and cars with a specified number of occupants (usually two, three, or four) the right to use a lane, a ramp, or an entire highway to the exclusion of all other vehicles.

Preferential treatment goes back a number of years with the first use being applied to transit vehicles. The first recorded preferential treatment for a bus was on North Sheridan Road in Chicago in 1939 and by the mid-1950's a number of other cities were also experimenting with bus preferential treatment. However,

[a]Presented at the April 14–18, 1980, ASCE Convention and Exposition, held at Portland, Oreg.

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on July 17, 1980. This paper is part of the Journal of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0263/$01.00.

TABLE 1.—1974 Fuel Consumption by Mode of Transportation[a]

Mode (1)	Consumption (2)
(*a*) Highway	
Passenger car and taxi:	
Gasoline[b]	1,756.43
Motorcycles:	
Gasoline[b]	10.64
Bus:	
Intercity	
Distillate fuel oil[b]	4.72
School	
Gasoline[b]	7.93
Local	
Gasoline[b]	0.18
Distillate fuel oil[b]	7.53
Liquefied gases[b]	0.07
Trucks:	
Single unit	
Gasoline[b]	502.98
Combination:	
Gasoline[b]	19.58
Distillate fuel oil[b]	220.92
(*b*) Rail	
Local	
Electricity[c]	2,630
Operating railroad	
Passenger	
Distillate fuel[b]	3.57
Electricity[c]	1,088.95
Coal[d]	1,041
Freight	
Distillate fuel[b]	96.41
Electricity[c]	401.10
Coal[d]	56
(*c*) Air	
General aviation	
Gasoline[b]	10.55
Jet Kerosine[b]	8.50
Air carrier	
Gasoline[b]	0.16
Jet-kerosine[b]	227.28
(*d*) Water	
Residual fuel oil[b]	91.12
Distillate fuel oil[b]	24.26
Gasoline[b]	16.59
(*e*) Pipeline	
Natural gas[e]	668,792

TABLE 1.—*Continued*

(1)	(2)
Gasoline reported to FHWA other than used for highway, aviation, or water[b]	81.55

[a]Sources: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook*, Washington, D.C., annual; U.S. Department of Transportation, Federal Highway Administration, Highway Statistics, Washington, D.C. annual; Tables MF-21 through MF-26 and Table VM-1, American Public Transit Association, *Transit Fact Book* '75–'76 ed., Washington, D.C., p. 45; B. V. Cayce, U.S. Department of Transportation, Federal Aviation Administration, *FAA Statistical Handbook of Aviation*, Washington, D.C. annual; Part 1—Table 31, American Public Transit Association, *Transit Fact Book*, Washington, D.C., annual; p. 45; W. F. Gay, U.S. Department of Transportation, Transportation Systems Center, *Energy Statistics*, Cambridge, Mass., 1976, p. 117.

[b]In millions of barrels.

[c]In millions of kilowatt-hours.

[d]In millions of tons.

[e]In millions of cubic feet.

it was not until the first Arab oil boycott of 1973 that preferential treatment for high occupancy vehicles became an accepted transportation operational technique. During the past 8 yr there has been a multitude of preferential treatment projects implemented around the nation. They have varied in scope, magnitude, imagination, and success. They have been debated in the courts and in the newspapers. They have received mixed reviews from highway planners and transit planners. In a similar manner, the general public has had divided views depending upon whether they used or did not use the HOV facilities.

A number of studies over the past decade have documented the fuel savings potential of high occupancy vehicles. In the report *Transportation Energy Conservation Options* (1), the authors indicated that carpooling for work trips could ultimately save 10.0% of total transportation fuel consumption. This was second only to auto-efficiency improvements.

A second report *Guidelines to Reduce Energy Consumption Through Transportation Actions* (2), also found that carpool programs and high occupancy vehicle facilities provided significant energy savings potential on the order of 10% or more. In this study only restrictive measures proved to have more energy savings potential. These included such measures as gas rationing, 4-day work week, and congestion tolls.

Data from individual HOV projects have shown the potential savings on a project basis. For example, when the Shirley Highway was carrying 1,815 carpools/day it was estimated that over 2,000,000 gal of gas was being saved annually (3). Now with carpools more than double that figure, gasoline savings are over four million gallons annually.

The Evaluation Report (4) for the Route 101 (Marin County) bus carpool lanes indicated annual fuel savings of 250,000 gal while on a lesser scale, the Santa Monica Freeway Diamond Lane project (5), during its last few weeks of operation, was saving 185 gal/hr or a savings of approx 0.8% over a preproject levels.

Preferential treatment projects have the potential of saving energy in two

ways. The most significant savings come from reducing vehicle trips by increasing auto occupancy. Thus, if two neighbors who work at the same location drive together rather than in their individual cars, their work trip energy consumption can be cut in half. Secondly, if their trip can be made at a more uniform speed with fewer stops then less fuel is also consumed.

There are potential increases in fuel consumption also. The automobile left at home may get used by other members of the family. The users of preferential treatment projects may take longer distance trips to save time than they normally would. Some preferential treatment projects may affect the normal movements of low occupancy vehicles causing them to consume more fuel. However, these latter items appear to be minor compared to the potential savings. There appears to be little doubt at this time that ride-sharing in general and preferential treatment projects in particular can save energy.

This conclusion is reiterated in a Congressional Budget Office Report (6) that stated:

> A typical mile of travel diverted to carpools saves more energy than does diversion to any mode other than vanpools. Unlike vanpools, for which the potential market is very small, carpools could be used for a large share of all commuter travel.

Actions to Increase Carpooling

Having proven the premise that carpooling can decrease our use of transportation energy, we, as engineers, need to consider the actions that can be taken to increase the amount of ride-sharing that goes on. Basically the actions fall into two categories: (1) Provision of preferential treatment facilities; and (2) policy and Management Action.

Preferential Treatment Facilities.—Over the past decade there have been a large number of projects which have provided all or part of a highway for the exclusive use of carpools or transit vehicles, or both. The nature of these projects range from the designation of a curb lane during the peak period as an HOV lane to the designation of a physically separated highway as an HOV facility. Experience has shown that the most successful physical facilities in terms of increasing the number of carpools are those that do provide a physically separate facility for exclusive use of carpools, or buses, or both, in a highly utilized urban radial corridor. Thus, the Shirley Highway (I-395) in the Washington, D.C. metropolitan area and the San Bernardino Busway in the Los Angeles area are the shining stars in the HOV world. These facilities are expensive to construct and require substantial time in their planning and implementation. Nonetheless, if we are to achieve significant energy savings over the next several decades then we must get serious about providing this type of facility.

With regard to construction costs which are significant, we must keep in mind the equivalent cost of comparable transit facilities. The Shirley Highway express lanes in the Washington, D.C. area were originally designed to be reversible lanes open to all traffic although after the highway was rebuilt, the lanes were reserved for buses initially and latter for any vehicle carrying four or more persons. When the Shirley Highway express lanes were constructed in the early 1970's, they added approximately $5 million per mile to the cost

of the upgraded Interstate. On the other hand, the Washington Metro system now being constructed is costing $50,000,000/mile–$70,000,000/mile. In addition, unlike the transit system, the carpools using the express lanes are unaffected by strikes or similar factors.

The writer would like to suggest that we need a major program for developing physically separate HOV facilities in all major urban corridors. The Federal government should adopt a policy of realistically evaluating HOV facilities in each urban corridor that is being considered for upgrading for either transit or highway improvements. To some extent, the Federal Highway Administration/Urban Mass Transit Administration Alternatives Analysis requires this consideration. However, my observations of the results of many of these analyses lead me to believe that we are still paying only lip service to the true effectiveness of the separate HOV facility.

In approx 3 yr we'll have a chance to evaluate what I believe is the most innovative idea in highway transportation in the last half century. This is I-66, a 10-mile long interstate facility, in the Washington, D.C. area that will be limited to four person carpools and buses in the peak direction during the peak period. Interstate 66 has been on the drawing board for over 2 decades. Like most urban freeways it spent much of this time in litigation. It could easily have died. Fortunately it survived, not as the eight-lane freeway that the demand estimates of the 1960's indicated was warranted, but as a four lane facility for the exclusive use of carpools and buses. Traffic forecasts have indicated that the two-lane facility will carry more people than would its eight-lane predecessor. The energy saving potential of I-66 are huge and should match those of Shirley Highway.

We need more I-66's. We need a strong Federal, state, and urban commitment to physically separated high occupancy facilities. In additional to saving energy, they reduce pollution, allow for more high density development in our central cores and reduce the transit deficits in all our communities.

Policy and Management Actions.—There are a host of policy and management actions which can be taken to complement and supplement the provision of physical facilities. Some of these actions may be counter to some of the early tenets of transportation planning. The following considers several of these.

Zoning Ordinance Required Parking.—There is a need to review the parking requirements in our zoning ordinances. Most of these requirements go back to the 1950's and 1960's when gas was cheap and transit ineffectual. Conditions have changed. To require developers to provide parking spaces based upon an earlier set of conditions is not only wasteful, but self-defeating. Most developers have a very good understanding of how much parking is required to satisfy tenants and will provide that number of spaces. However, in many cases the zoning ordinances force the developer to provide more than is needed, adding costs to the development which are merely passed on to the tenant and the consumer. A reduction in the number of spaces coupled with incentives to encourage high occupancy vehicle use should be permissable in all zoning ordinances. This reduction should be granted within reasonable distances of transit stations (bus or rail), high occupancy vehicle facilities, or where the developer comes up with a transportation management program to provide for the needs of all users of his building at acceptable levels of service. Often, this type of reduction is opposed by the surrounding neighbors who fear a

spillover of parking into their neighborhoods. This is a valid fear, but the residential parking permit program which has been declared legal by the courts, has provided a solution to this problem.

Level of Service Design Criteria.—There is need to review the criteria that transportation planners use to evaluate urban facilities. In the 1960's, Level of Service "C" was the standard for most urban designs. Within the last several years, however, most agencies have adopted Level of Service "D" as the standard. I wonder if we have gone far enough? As you know, level of service is a criteria we apply to the peak hour. Therefore, if we use Level of Service "D" as the design criteria, we are saying that in most cases the street or highway will operate at Level of Service "C" or better for approx 22 h of the 24 h. This is great if you happen to be a driver. But is this good for our urban areas in total?

A recent proposal (7) by the Montgomery County Office of the Maryland National Capital Park and Planning Commission (MNCPPC) would seem to say that it is not in the public's interest. MNCPPC is proposed that certain high density urban areas be designated in a special zone where Level of Service "E" would be the design standard. An excerpt from this proposal follows:

> The standard of service proposed would tolerate up to twenty percent of the daily trips experiencing LOS E or worse. This would mean that those conditions would last from one and one-half to two and one-half hours each day (divided between the morning and evening commuter rush periods) on the beltway, major radial and arterial highways, cross-county highways, and at the intersections of such roads. Some pressure would also exist on selected streets within the central business districts. The standard is set high enough, however, to avoid serious spillover of traffic onto neighborhood streets.
>
> The standard of service for Group V areas is designed to operate the road system to its maximum capacity during peak periods. However, approximately 80 percent of the daily trips will travel in conditions of Level of Service "D" or better.

In essence, they are saying that we should recognize that one characteristic of an urban area is high density and that high density may cause congestion at certain times. Given the other goals that we achieve through high density urban areas, short periods of congestion may be a price worth paying.

I would like to say that I fully agree with this new concept. In my mind, it does several things. It will achieve greater utilization and efficiency from our streets and highways. Level of Service "E" is that point at which the most number of vehicles can move on a highway. The congestion will, no doubt, result in some low occupancy vehicle users switching to transit, carpools or vanpools. The congestion may force employers in the area to develop TSM measures to avoid increased congestion. If these programs include incentives for HOV's, staggered working hours, and the provision of subsidized transit passes, all the better.

This may seem heresy for a transportation engineer to suggest that a little congestion may be in the public interest, but with gasoline approaching $1.50/gal

and $2.00/gal a short term certainty rather than a long range pipe dream, some unorthodox thinking is done.

Employer Incentives for High Occupancy Vehicles.—It's time that employers considered what incentives they can provide for HOV's. Some have already begun to do so. Much more can be done. Some of these would include the following.

Employer Subsidized Transit Passes.—In years past many employers have provided free or cheap parking to its employees. This should be phased out and replaced by carpool and vanpool parking and by free or subsidized transit passes. Everyone gains in this policy. Less energy is consumed, the employer can probably get away with less parking (as was the case with 3M in St. Paul, Minn.), there is less congestion, transit subsidies are reduced and there is probably less absenteeism and better employee morale. Enlightened employers around the nation have begun to provide subsidized transit passes. They should be encouraged through tax benefits and publicity.

Other HOV Incentives.—There are other actions that can be taken to encourage the use of HOV's particularly with vanpools. Employers can provide the financial and administrative backing for the purchase, lease and management of the vans. The employees responsibility would be the selection of an individual who would act as a driver and caretaker of the vehicle for which he gets free commutation and has the option of renting the vehicle during noncommute times. Other employees would pay a fee based upon the monthly cost of the services. These arrangements are becoming more commonplace, but it is evident that the key to successful vanpooling is an employer who actively favors and markets the program. Without this active support, vanpool programs will have limited success.

Employers should also take an active part in matching employees for both carpools and vanpools. Most metropolitan areas have carpool matching programs on a regional basis. However, the most successful programs involve employees of the same agency or in the same building complex. Likewise, the potential users of the matching services are more comfortable when their fellow riders are from the same neighborhood or share the same employer. Employers should encourage their new employees to join carpools by assisting them in finding individuals with similar commuting patterns.

In addition, employers should give preferential parking to carpools and vanpools. These parking spaces should be desirable spaces close to the facility. A reduction in cost for the space is not necessary since the per person parking cost will be lower due to the number of occupants.

Some of the aforementioned actions along with other even more stringent requirements are contained in the Department of Energy's Standby Federal Energy Conservation Plan as required by the Emergency Energy Conservation Act of 1979. This plan, now in the review stage, would include the following actions once the President has declared that an emergency exists:

Employer-Based Commuter and Travel Measures.—Employers (non-Federal government) with 100 or more employees per work-site would be required to develop for each affected work-site a program to reduce work-related travel by employees, including home-to-work travel. An example of a specific strategy that might be included in an employer's travel reduction program is reducing the availability of parking for *single-occupant* vehicles at work-sites or reducing the employer-provided parking by 20%.

Vehicle-Use Sticker Measure.—This measure would require all private and business owners of gasoline and diesel-powered motor vehicles to forego use of their vehicles for 1 day/week, 2 days/week, or 3 days/week, depending upon the shortage. Under this measure, owners would be required to afix to their vehicles stickers indicating, by color, symbol or other characteristic, the day or days on which driving is prohibited. Individuals and businesses that rent or lease vehicles on a sequentially repeating, continuing, or long-term basis would have the same responsibilities as vehicle owners. The choice of specific days of the week on which vehicle-use prohibitions apply will be a collective decision of the individual vehicle owners of a given household. Included in the list of vehicles exempted from this measure are *vanpool vehicles* that are formally registered with a coordinating or state-designated agency. These measures may seem out of place in our free enterprise American society but it is indicative of the nature of the energy crisis that we are contemplating such activities.

Conclusions

The energy crisis that we face in this country is real and transportation will continue to be directly impacted by the crisis. The economics of the marketplace have already brought about some changes in our travel habits but it is clear that in the range of fuel price changes which we have seen thus far, demand for fuel is relatively inelastic. Prices will have to increase substantially from their current values to see major decrease in demand. The changes that have occurred thus far have resulted in savings in energy. Transit usage was up approx 7% in 1979 over the previous years' totals, approx 7% in 1979 over the previous years' totals, the largest single annual increase since World War II. Given the limited market that transit has in many of our urban areas, the lead time required to increase transit supply along with the vastly increased cost of transit service, the greatest energy savings in transportation will come from increased use of carpools and vanpools.

The energy saving potential of carpools and vanpools is substantial. Studies have indicated that a ten person van saves upwards of 8,800 gal of fuel annually and that a four-person carpool saves 800 gal/yr. These are major savings and worthy of pursuit. They can be achieved over a period of years by vigorous actions at all levels of government and private industry. These actions should include:

1. A major Federal program to provide physically separate HOV facilities in high density urban radial corridors.
2. A program to reduce the required parking in major employment centers.
3. A program to review level of service standards for highly urbanized areas.
4. A program to encourage incentives for carpools, vanpools and transit through preferential parking, matching services, administrative services for vanpools and employer subsidized transit passes.

These complementary actions will result in the long term achievement of greater transportation energy efficiency without serious impact on our nation's mobility.

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TRANSIT OPERATING STRATEGIES: TENTATIVE GUIDELINES

By David Spiller[1]

(Reviewed by the Urban Transportation Division)

INTRODUCTION

The last several years have seen a major change in transportation planning. The current emphasis is on the better use of existing facilities through the implementation of transportation systems' management techniques (TSM). This is reflected in the increased research activities of the Transportation Research Board (5), in such demonstrations as the Shirley Expressway exclusive bus lane (8), or Boston's "Downtown Crossing" auto restricted zone (2), and in the formal planning requirements issued jointly by the Urban Mass Transportation Administration and the Federal Highway Administration for all urban areas (1). These few examples are illustrative of a much broader spectrum of TSM actions which emphasize low-cost options for the better use of public and private transportation facilities.

A related concept to TSM is a generic class of actions or strategies that can be applied to transit systems. The objectives of this paper are to: (1) Define and distinguish transit operating strategies from a larger family of transportation systems' management techniques; (2) to identify and classify sets of transit operating strategies; and (3) to develop heuristic guidelines for implementing them. The latter objective raises the important questions of what problems each strategy is most suitable to address, and what are the likely impacts on the system when implemented.

DEFINING TRANSIT OPERATING STRATEGIES (TOS)

A transit operating strategy shall be defined as an action or set of actions that affect the state of the system within the time frame of one hour. Thus, in general, the following assumptions or constraints apply.

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on July 23, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0273/$01.00.

1. Route configuration is fixed.
2. Station spacing is fixed.
3. No new resources, e.g., equipment or men, are created, and some existing resources may be inoperable.
4. No outside agency's cooperation or legal sanction is required for the transit operator to take action.

Both the definition of a TOS and these assumptions distinguish a transit operating strategy from a transportation systems' management option and therefore TSM options applicable to transit systems such as signal preemption, exclusive

TABLE 1.—Classification of Transit Operating Strategies

Variable (1)	Fixed guideway (2)	Bus systems (3)
(*a*) Station-Stop Policies		
Skip-stop service	X	X
Express service	X	X
Zonal service:		
Shortening and lengthening of routes		X
Running trains "short"	X	
Tactical use of crossovers	X	
(*b*) Entrainment Policies		
Double platform length trains	X	
"Banking" of vehicles	X	
(*c*) Dispatching Policies		
Holding points	X	X
Vehicle and crew reassignments among routes	X	X
Line sequence changes on shared rights-of-way	X	X
(*d*) Other Transit Operating Strategies		
Platooning of vehicles into "convoys"		X
Demand modification—passenger discouragement by providing information on expected service levels to passengers at stations	X	X

busways, institution of park-n-ride facilities, pricing changes, or flow metering are excluded from consideration.

Identification and Classification of Transit Operating Strategies

Based on these constraints, Table 1 presents a taxonomy of transit operating strategies applicable to either or both fixed guideway transit systems and to bus systems. In general, transit operating strategies can be classified under four headings: (1) Station-stop policies; (2) entrainment policies; (3) dispatching policies; and (4) other.

General Planning Principles

Ultimately, the successful implementation of a transit operating strategy depends upon a clear understanding of the problems that such strategies are designed to address, as well as upon a clear delineation of goals, objectives, and service performance standards.

The general class of problem for which transit operating strategies are particularly well suited is any sudden perturbation to the steady-state operation of the transit system or to any element of the system. Such a "shock" can come about as a result of a sudden surge in demand at a station, along a route or corridor or even network wide, a blockage on a fixed guideway system, vehicle breakdowns, schedule unreliability due to congested surface traffic conditions, or adverse weather conditions affecting operations, particularly with regard to vehicle cycle times.

This is not to deny that many of the transit operating strategies identified in Table 1 should also be considered within the planning, design, and operation phases for transit systems. But it is for the sudden "shocks" to the normal operation of the transit system that transit operating strategies are designed.

Service performance standards for transit service include such level of service factors as accessibility, travel time, schedule adherence, frequency of service, loading, and cost of service to user and operator (4,6). In light of the four constraints affecting transit operating strategies and the short duration during which the system must react to TOS implementation, two LOS factors are particularly relevant: (1) Passenger loading; and (2) passenger wait times. The latter directly relates to schedule adherence and transit headway policies. Accordingly, alternative TOS performance standards which can guide the selection and implementation of a transit operating strategy might include the following.

1. Setting a maximum loading limit at the maximum load point as a percentage of the seated capacity of the vehicle in use on a route.
2. Setting a maximum waiting time constraint.
3. Equalizing waiting times.
4. Allowing waiting times above a tolerance limit to the fewest number of passengers.
5. Equalizing shortage of capacity among routes, i.e., a proportionate reduction in capacity among routes taking into consideration route length and travel times as well as headways.
6. Establishing priority service to a subset of routes.

Implementation and Impacts

Station-Stop Policies: Skip-Stop Service.—Skip-stop service is the operation of a transit vehicle on a transit route at only a specified subset of station stops. There are two possible variants of skip-stop service depending upon when and where the service is implemented. If control is exercised at either of the two terminal ends of the route, then a designated subset of stops can be specified for which no passenger boarding or alighting is allowed (see the section on express service). If, however, the service is executed enroute, then only passenger loading can be prohibited at designated skip-stop stations down-

stream from the point at which a decision was made to implement the service unless a secondary decision is made to require onboard passengers destined for skip-stop stations to transfer to a succeeding vehicle.

Implementation Guidelines.—Several considerations should guide the implementation of skip-stop service enroute. These factors include the level and duration of passenger "crush" loads on the vehicle (usually the "crush" load is defined as 150% of the seated capacity of the vehicle) and the expected number of passengers waiting to board the vehicle at designated skip-stop stations.

Skip-stop service is designed to relieve extreme crowding conditions on the vehicle by prohibiting additional loading of the vehicle; as a result, the onboard passenger count is a nonincreasing function of the vehicle's position. This is shown graphically in Fig. 1 where the onboard passenger count at the $j-1$ and jth stop, O_{j-1} and O_j respectively, is presented as a function of run time on the route for normal and skip-stop service. In addition, a_j and b_j represent alighting and boarding rates respectively at the jth stop, where it is assumed that skip-stop service has been implemented to the end of the route. Onboard

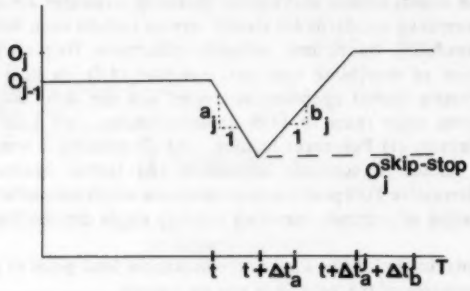

FIG. 1.—Onboard Passenger Count between Stations $j-1$ and $j+1$

passengers' travel times are moderately improved due to the reduction in dwell times from limiting service at the designated skip stops.

The increase in passenger utility resulting from a reduction in crowding conditions and a potential increase in effective vehicle running speed, however, must be balanced by an increase in waiting time equal to the headway of vehicles on the route under prevailing traffic conditions imposed on passengers at the designated skip stops. It also cannot be assumed that the impact on passengers awaiting service at the designated skip stops is uniform among these stops. The dwell times of the following vehicle on the route will increase so that the sequence of headways between successive vehicles which actually stop at these designated skip stops of the control vehicle's run form a nondecreasing sequence. Therefore:

1. Designated skip stops should be major trip destinations. Conversely, designated skip stops should not be major origination points unless the vehicle loading is at crush condition for a relatively long duration (see the following).

2. Passenger loading prior to implementation should exceed crush conditions for n successive stops or a duration of τ minutes, whichever event occurs first. Determination of the values for n, τ depends upon balancing the benefits to onboard passengers against the costs to potential passengers downstream; for a first approximate iteration, a reasonable set of values for n, τ might set n equal to three stops and τ equal to 5 min.

3. If skip-stop service is to be implemented for successive vehicle runs along the route, the designated set of skip stops for each vehicle run should form a disjoint set, i.e., vehicles should not skip the same stop between successive vehicle runs along the route otherwise extremely long waiting times are imposed upon potential passengers serviced by that stop.

4. A vehicle under skip-stop service should exceed a specified headway tolerance. Simulation studies show that the tolerance limit must be fairly high, e.g., 125%–135% of scheduled headway, if skip-stop service is to be effective at least in providing a more uniform or regular service along the route (3).

Express Service.—When control is exercised at either of the two terminal ends of the route (or any point commonly used as the dispatch point on the route), then a specialized form of skip-stop service, namely an express service, can be implemented. Under express service, no boarding or alighting is allowed at a designated set of stops.

Implementation Guidelines.—Two decisions must be made before express service can be implemented: (1) Under what circumstances; and (2) to what station should vehicles run express. These decisions are interdependent, for the nature of express service, in prohibiting boarding and alighting over a subsegment of the route, suggests that the choice of first station stop under express service ought to be that station which maximizes vehicle occupancy over this subsegment. Therefore:

1. A large surge in passenger demand must be present at the originating dispatch point. This increases the likelihood of achieving high vehicle occupancy by providing an express service since each downstream station has a larger pool of potential passengers for which that station represents a trip end.

2. The first station stop on the express run should be chosen as that station which maximizes vehicle occupancy over this subsegment of the route.

3. The express run subsegment should be as long as possible, consistent with the best choice for the first station stop, in order to exploit the maximum cruise capabilities of the vehicle. For fixed guideway systems, this implies that a minimum headway sufficient to clear the forward blocks of preceding vehicles ought to be maintained at least over the express run subsegment of the route. In practice, guideline two and three may be in conflict so that tradeoffs will have to be evaluated in order to achieve the overall best results consistent with the transit operator's objectives.

4. Sufficient vehicles ought to be available to provide local service at the dispatch point within a reasonable headway following the express run(s).

Zonal Service.—Zonal service involves the partitioning of the transit route into a set of discrete usually nonoverlapping zones and reassigning vehicles to service the designated stops within one or more zones rather than cycle

over the total length of the route. There are several variations of this type of service. One variation is to allow vehicles to service stops within the first zone as part of a collection phase, then run nonstop to a final zone commencing a distribution phase.

The classic and simplest variation of zonal service is the case of shortening the route, or in the case of fixed guideway systems "running trains short," making tactical use of existing crossovers. Under this type of zonal service, transit vehicles cycle between a subset of the designated stops on the route, usually the initial dispatch point and a downstream station at which vehicles can be turned back. In the general case, however, the vehicle may cycle between two specified stops on the route neither of which are the two normal dispatch points or termini of the route.

Only this latter variation of zonal service is considered herein.

Implementation Guidelines.—The objective of running vehicles "short" is to reduce the vehicle's cycle time thus decreasing the headways and increasing the level of service provided passengers over the shortened segment of the route. For fixed guideway systems, the ability to run trains "short" is constrained by the track geometry configuration, specifically the existence and location of crossovers between inbound and outbound tracks. (For transit designers, this suggests that maximum operational flexibility can be achieved at relatively little marginal increase in cost and complexity by providing multiple crossovers in the track layout at strategic locations.)

The tradeoff in pursuing this policy is that passengers whose trip ends lie beyond the shortened route subsegment suffer a deterioration in level of service involving increased waiting time, transfers to another vehicle serving their destination, or both. Therefore:

1. There should be a large surge in demand at one or more designated station stops with trip destinations clustered over a relatively short distance.
2. For fixed guideway systems, trains switched onto the crossover should be dispatched in the reverse direction at a time t_o equal to one half the normal headway interval for trains in the reverse direction past that point.
3. The designated station stop for short operation should allow for safe, nondisruptive vehicle turnaround.

Entrainment Policies: Double Platform Length Trains.—For fixed guideways, the platform length of the most restrictive station on the line defines the maximum number of vehicles that can be coupled under normal operation, i.e., running the length of the line. It is possible, though, to couple vehicles to achieve a train length which is an integral multiple of the platform length, for example double the platform length.

Trains operating in this mode would have to load and unload twice at each station, i.e., the first set of coupled vehicles would load and unload passengers, then proceed downline a distance equal to the platform length to allow the latter set of coupled vehicles in the trainset to commence loading and unloading. Under conditions of skip stop or express service, the increased dwell times under this strategy can be substantially alleviated.

Implementation Guidelines.—Double platform length trains, coupled with skip-stop or express service, should be implemented only under the following

restrictive circumstances: The accumulation of passengers into one or more stations should exceed the holding capacity of the station(s), particularly when minimum headways are in operation for the line in question and can therefore not be reduced. This is shown in Fig. 2 which shows the accumulation of passengers, $\lambda_i h_i$, and overflow queues not serviced by trains dispatched at minimum headways h_i. In addition, C_o and Q represent the holding capacity of the transit station, and the passenger overflow queue respectively.

The additional dwell times and increased length of the train will affect the signal operation by increasing block occupancy time with spillover to trailing blocks. As a result, a moderately higher minimal sustained headway will occur. However, this transit operating strategy can prevent under most circumstances the buildup of queues and extreme crowding within the holding areas of the

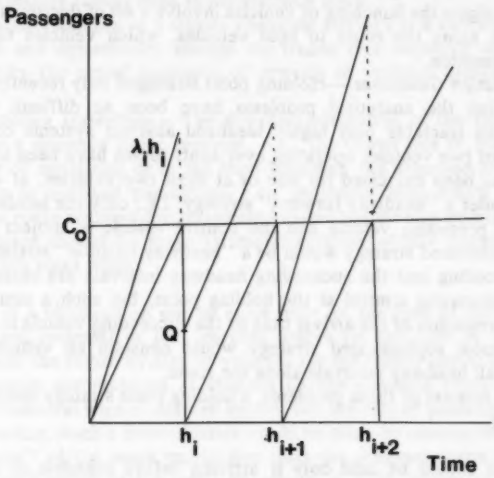

FIG. 2.—Passenger Arrival and Service Process at Congested Transit Station

station even accounting for the accumulation of passengers during the longer dwell times at the stations. A good example of where this transit operating strategy might be useful is the case of a major sporting event providing rapid exiting of passengers to transit stations.

"Banking" of Vehicles.—Under a transit operating strategy of "banking," a trainset of an unequal number of coupled vehicles is operated in each direction during a train cycle over the route, thus, a surplus of vehicles is accumulated at one of the dispatch points.

Implementation Guidelines.—Implementation of "banking" as a TOS ought to be guided by the following.

1. Passenger demand oriented in one direction, or reversible at different times of the day or both, e.g., typical commuter patterns, sporting events, etc.

2. Off-peak implementation in anticipation of a passenger surge in demand in a predominant direction.

3. To provide priority service, i.e., reduced headway intervals using smaller trainsets, in one direction as for example to service shopping trips to the CBD during the off-peak period.

Dispatching Policies.—Dispatching policies consist of the exercise of headway control on a transit route. The objective is to reduce waiting times for passengers by providing for a more uniform flow of transit vehicles on the route. Dispatching policies include holding point strategies which are not particularly well understood, equipment and crew reassignments, and line sequence changes on shared rights-of-way.

Holding Point Strategies.—Holding point strategies which are designed to prevent or mitigate the bunching of vehicles involve a set of decisions concerning which points along the route to hold vehicles, which vehicles to hold, and how long a duration.

Implementation Guidelines.—Holding point strategies only recently have been studied (7) but the analytical problems have been so difficult that to be mathematically tractable only highly idealized abstract systems consisting of one or at most two vehicles operating over short routes have been looked at.

Control has been exercised for one or at most two vehicles, at one holding point, and under a "headway forward" strategy, i.e., only the headway interval between the preceding vehicle and the control vehicle is subject to control. A more sophisticated strategy would be a "headway balance" strategy whereby both the preceding and the succeeding headway intervals are searched in the process of exercising control at the holding point, but such a strategy would require the prediction of the arrival time of the succeeding vehicle at the control point. The most sophisticated strategy would consider all vehicles and the sequence of all headway intervals along the route.

Within the context of these problems, a holding point strategy should consider the following.

1. Vehicles should be held only if arriving before schedule at the holding point.

2. Vehicles should not be held if the loading of the vehicle at the time of arrival at the holding point exceeds the seated capacity of the vehicle.

Equipment and Crew Reassignments.—This is the policy of transferring or reallocating vehicles across routes to provide different headway interval service than under normal transit operation.

Implementation Guidelines.—Equipment and crew reassignments involve a deliberate decision to give priority to a subset of routes at the expense of other routes. Rational implementation of such a policy implies that the gains in service to the favored routes ought to substantially exceed the reduction in service to the other routes. Thus:

1. Routes subject to vehicle and crew reassignments should be closely spaced to minimize deadheading and to effect an immediate implementation of the policy.

2. The passenger arrival rates at stations along a transit route should substantially exceed normal expectation, and should be sustained over several vehicle runs.

3. The reduction in service from the removal of vehicles should be distributed over as large a set of routes as possible, i.e., choose a set of routes and vehicle reassignments to minimize the maximum reduction in service to any one route (minimax strategy).

Line Sequence Changes.—Under normal operation, transit lines which share their right-of-way over a portion of their route are dispatched independently. The sequence of vehicles corresponding to each transit line past a stop on the shared route segment is dependent upon the sequence of arriving vehicles from the respective transit lines at the dispatch point.

Line sequence changes as a transit operating strategy is a deliberate decision to intervene and dynamically change the transit line sequence without being constrained by the actual sequence of arrivals of vehicles dedicated to each transit line.

Implementation Guidelines.—The dynamic adaptation of the transit line sequence over a common route segment, e.g., the Green line in Boston, serves the purpose of equalizing or at the least bounding the expected and maximum waiting time to nonlocal passengers, i.e., passenger trips which originate on the common route segment but terminate beyond the diverge points.

Consideration should be given to implementation of line sequence changes at the dispatch point when:

1. There is a blockage on one or more lines (in the case of fixed guideway, single channel systems) or long enroute delays (in the case of bus systems) which prevent the return cycling of vehicles for the transit line(s) in question.

2. Passengers accumulating at stations on the common route segment are dominantly nonlocal trips as defined herein, and the rate of passenger accumulation is increasing. Such a determination could be made by running two successive vehicle "runs" of the same transit line pass the common route segment and estimating the number of remaining passengers at each station on the common route segment.

Other Transit Operating Strategies.—Table 1 identified two other transit operating strategies: (1) Platooning of vehicles, and (2) demand modification.

Platooning is the policy of operating two or more uncoupled, independently controlled vehicles at a minimum safe space headway over the transit route. It is the analogue to the entrainment of vehicles on a fixed guideway system.

Platooning of vehicles is a useful transit operating strategy when there is a large surge in demand at one or more stations over a short duration thus requiring maximum loading capability, as for example commuter express runs from park-and-ride facilities. Platooning has the additional advantage of often increasing the effective speed of the transit vehicles.

Demand modification is a strategy of deliberately discouraging or curbing passenger demand at one or more stations. Good transit operations require that as a matter of policy, affected and potential passengers should be informed when there is a deviation from the normal level of service, and when normal

service might be restored. Such a policy protects the "goodwill" of passengers to the system as well as help relieve the short-run imbalance between passenger loads and the capability of the system to meet those loads within a tolerable level of service even after the implementation of other transit operating strategies.

Practical Applications

The exposure of senior supervisory transit personnel to transit operating strategies and some of the ramifications of their implementation can improve the emergency management of a transit system. Direct application of these guidelines would require information concerning passenger accumulation and wait times at stations, passenger loads on vehicles, deviations of vehicle arrival time from scheduled arrival time at strategic locations in the system, and vehicle availability. In addition, passenger trip patterns including the occurrence of special events should also be known, at least with respect to originating, terminating, and transfer stations in the system. It may be that some of this information is not currently and immediately available to transit operators.

Indicated areas for future research include the following:

1. The design of a data collection system and related technologies, including the use of trained observers, to support TOS implementation.
2. Additional analytical work predicting the response of a transit system to sudden "shocks," followed by TOS implementation leading to a revised set of guidelines.

Summary and Conclusions

Transit operating strategies are designed to address problems that result from sudden "shocks" to the normal operation of a transit system. Often, because of the constraints and environment under which a transit operating strategy is implemented, the gains in level of service to some passengers are partially offset by losses in level of service to other passengers. In this sense, TOS implementation operates on a Pareto-optimal frontier characterizing the efficient normal operation of the system; no control action taken by the transit operator can result in utility gains without some offsetting losses.

However, TOS implementation under some circumstances can make everyone better off. Nevertheless, implementation of a transit operating strategy can result in a better system-wide operation, allowing for interpersonal tradeoffs, and prevent the progressive deterioration of service that would result from no control actions.

The implementation guidelines developed in this paper are tentative; the intent of the guidelines is to improve the search process in devising control responses to various problems arising from a sudden "shock" to the transit system. No attempt has been made to optimize the operation of a transit system under nonsteady-state conditions, and it may be that some of the guidelines require data which are not readily available to transit operators now. It is hoped that future research can remedy this problem, and that the implementation guidelines can assist transit personnel to search and subsequently implement "good" control responses.

Acknowledgments

The writer is grateful to John Schoon, Department of Civil Engineering, Northeastern University, and the reviewers whose comments have substantially improved the presentation of this paper. The views expressed herein are those of the writer and do not necessarily represent the position of the United States Department of Transportation.

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Appendix III.—Notation

The following symbols are used in this paper:

O_{j-1}, O_j = onboard passenger count at stations $j-1$ and j respectively, in number of passengers;
a_j = alighting rate at station j, in passengers per second;
b_j = boarding rate at station j, in passengers per second;
$\Delta t'_a$ = total alighting time at station j, in seconds;
$\Delta t'_b$ = total boarding time at station j, in seconds;

τ = duration of time, in minutes;
λ_i = passenger arrival rate during the ith time interval, in passengers per second;
h_i = ith headway interval, in seconds;
C_o = holding capacity of transit station, in number of passengers; and
Q = overflow queue length at transit station, in number of passengers.

TSM: What to Do About Urban Goods Movement?

By Walter J. Diewald[1]

(Reviewed by the Urban Transportation Division)

Introduction

Goods movement in urban areas is best typified by the truck; the truck is used to move goods around the city while the private auto and buses (and transit vehicles in some cases) are used to move people around the city. Urban transportation planning was initially preoccupied with auto movements; however, there is a current emphasis on the people-moving aspects of urban transportation systems and an increased understanding that further increases in vehicle-carrying capacity has become more and more difficult to provide. Throughout this transition urban goods movement (UGM) has been, and in many cases continues to be, accounted for by making use of passenger car equivalents, in spite of some very substantial differences between the two.

Some members of the planning and research communities have recognized the relevance and timeliness of a comprehensive approach to the analysis of UGM. They have accomplished some significant results, possibly aided by, as Redding put it, the fact that UGM does not encourage "the band wagon effect which attracts the type of person who is interested only in issues which are currently in vogue" (11). The work that has been completed takes on an added importance in view of new initiatives by the U.S. Department of Transportation which add emphasis to UGM within local efforts toward developing transportation systems management (TSM) actions.

This paper briefly describes the magnitude of UGM within the overall urban transportation system and highlights some of the major studies that have been completed in the 1970s with regard to UGM, emphasizing the results that are particularly relevant to TSM planning. It also examines some of the TSM-oriented literature and discusses what has been put forth as potential TSM actions relative to UGM activities.

The paper categorizes and summarizes the TSM/UGM actions, briefly exam-

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on July 22, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0287/$01.00.

ines the impact of other TSM measures upon UGM activities, and discusses some of the emerging developments which may impact UGM planning and operations during the 1980s.

Nature and Magnitude of UGM

As mentioned above, UGM is generally typified by truck movements, although it might also involve the use of passenger vehicles, as in the case of some service industry operations. UGM generally involves the intracity component of physical distribution but, in fact, can be interpreted as involving all such movements through urban areas, including any urban component of intercity goods movements. In any case, there is a broad range of industry segments or components which can be used to characterize the various types of goods and services comprising UGM; one study has provided the breakdown of 42 segments shown in the following list, within the industry (1):

1. Food.—General groceries (dry); Frozen foods; Milk, ice cream and other dairy products; Poultry products; Meats and meat products; Fresh fruits and vegetables; Canned and preserved fruits and vegetables; Bakery products; Sugar and confectionary products.
2. Beverages.—Beer; Wines and brandy; Liquor; Soft drinks.
3. Nondurables.—Tobacco products; Apparel; Drugs and drug proprietaries.
4. Paper products.—Paper and paper products; Printed products (except newspaper); Newspapers.
5. Consumer durables.—Furniture; Electrical appliances; Leather products; Instruments; Motor vehicles.
6. Building products.—Lumber; Cement and concrete; Brick and other clay products.
7. Energy.—Gasoline; Heating oil; Natural gas; Coal; Electricity.
8. Services.—Refuse; Laundry; Mail; Telephone; Surface parcel services; Air freight; Vending; Armored express; Appliance service.
9. Intermediate products.—Intermediate manufactured products and industrial goods.

This same study indicated that intracity goods transportation consumes nearly $57 billion annually; moreover the average annual increase for local trucking during the period 1966–1973 was more than 15%. It has been shown that urban trucks make up 15% of the total urban vehicle trips and a similar portion of total urban travel.

UGM trips tend to increase as the urban area increases and the population density decreases. As density decreases, commercial centers are located further apart since their spacing is based upon population. Therefore with a decline in density, trip length and truck activity (trips) will increase. Just how much of the UGM travel can be reduced is yet to be determined since the urban freight industry is a highly fragmented assembly involving many participants. Characteristic of this fragmentation is the fact that one-half of all fleets with more than one vehicle operate fewer than five vehicles; 75% of all fleets operate fewer than 20 vehicles (14).

In seeking solutions to UGM problems it must be noted that, for the most

part, there is no areawide UGM problem. It seems logical that high density land uses will be the most likely source of UGM-related problems, particularly if the UGM activities are competing with other pedestrian and vehicular activities for limited street space. A study of UGM problems in six cities noted that "each city tended to have its own unique set of localized problems" (3). This leads to the inevitable conclusion that, like many urban transportation program elements, solutions to UGM problems may well rely more on better professional judgment than on improved analytical techniques. Nevertheless, although past and current UGM research and planning efforts have accomplished much, there remains much more to do in order to provide a satisfactory planning base for UGM.

Highlights of UGM Research in the 1970s

The first major research effort directed toward the study of urban goods movement and sponsored by the U.S. Department of Transportation (DOT) was initiated in 1971; the purpose of the study was to explore the nature and magnitude of the transportation and environmental problems related to the movement of goods in urban areas (15).

The study resulted in the identification and assessment of nine means of improving upon five specific problem areas impacting upon shippers, carrier consignees, and the general public. Table 1, excerpted from the final report of that study, illustrates an assessment of the potential impacts of the improvements or project options upon four of the five problem areas. The fifth problem

TABLE 1.—Potential Impacts of Selected Project Options on Urban Goods Movement Problems (15)

Project options (1)	Problem			
	Reduction in costs and/or increase in profits (2)	Relief of truck-induced congestion (3)	Reduction in truck air and noise pollution (4)	Effective integration in urban development (5)
Urban freight consolidation	Modest	Major	Major	Major
Standardized shipping units	Minor	Minor	None	None
Spatial separation of goods/people movement	Modest	Major	Minor	Minor
Temporal separation of goods/people movement	Minor	Major	Minor	None
Off-street loading and unloading facilities	Negative	Major	None	Modest
Urban fringe terminal system	Modest	Modest	Modest	Major
Combined passenger/freight movement	Modest	Major	Major	Major
Automated systems for goods movement	Negative	Major	Major	Major
Automated terminal operations	Minor	None	None	None

area, institutional arrangements, was examined as follows:

> It should be recognized that these nine options all directly involve urban goods operations or facilities; identification of planning and administrative needs are subsumed implicitly within them. These latter needs include improvements in forecasting demand for goods movement (indeed, to be able to describe the demand for goods movement today would be a major achievement), regulation, documentation, and infrastructure arrangements. While these needs are important and current practices appear to be lacking, their function is purely supportive—to facilitate the design, implementation, and maintenance of goods movement operations.

The study made only three recommendations. They were the following:

1. The Department of Transportation (DOT) should undertake the design of an experimental plan for the demonstration of an urban consolidated freight system.
2. The DOT should undertake an analytical investigation of the effects of alternative types of traffic restrictions on goods movement efficiency and on improvements in traffic flow.
3. The Urban Mass Transportation Administration (UMTA) should undertake an investigation of the practicality and potential benefits of the joint use of exclusive traffic lanes by buses and trucks.

Two major subsequent studies provide additional insight into the nature and magnitude of UGM problems as well as potential solutions. The first of these two studies was entitled "Urban Goods Movement Demonstration Project Design" and had as its objective to define quantitatively and qualitatively the impact of goods movement in urban areas on goods movement costs, traffic congestion, energy consumption, air pollution, noise pollution, and lands use and to formulate potential solutions to those situations where the impacts presented problems (1). The results of this study further clarified the extent and magnitude of UGM and its impact upon urban activities. For example, it was estimated that "the cost of goods movement within cities is substantially more than intercity truck, rail, air, or water expenditures individually and is nearly as large as all intercity freight transportation combined." Moreover it was concluded that cost is the most prominent impact of UGM on the urban community, followed, in terms of importance, by congestion, energy consumption, and air pollution. Table 2 summarizes information from the study regarding the key opportunities or actions for improving UGM or reducing undesirable impacts.

The second study provided a useful UGM guide for traffic engineers and transportation planners in addressing short-range engineering and planning needs associated with urban trucking. The guide presents a range of analytic techniques as well as improvement suggestions which are predominantly low-capital traffic engineering improvements (14).

The three major studies which have been discussed above illustrate the general evolution and direction of UGM-related research, from preliminary analyses and assessment to specific improvement suggestions. Many other significant

accomplishments have been achieved, as evidenced by the work of the Urban Goods Movement Committee of the Transportation Research Board, the three national UGM conferences sponsored by the Engineering Foundation, and the growing list of studies and published reports related to UGM.

It appears that the basic framework for solution options and solution impact remains much the same as originally outlined in 1971 and represented in Table 1. There nevertheless remains much work to be done in the area, especially in view of escalating effects of rising fuel and labor costs and the reduced capability to find solutions through large capital expenditures. Robert Redding's comment at the 1975 Conference on Goods Transportation in Urban Areas that "the subject is underdeveloped and offers challenges and opportunities for many

TABLE 2.—Summary of Key Opportunities for Improving UGM or Reducing Undesirable Impacts From Ref. 1

UGM action goal (1)	Suggested UGM action (2)
Cost reduction	Improve management; Increase delivery lot sizes; Reduce institutional constraints to efficient operation
Reduce congestion	Temporal separation of goods/people movement; Enforcement of no-parking and no-stopping regulations; Improved loading dock and loading zone facilities
Reduce petroleum use and air and noise pollution	Reduce absolute number of miles driven; Increase average vehicle speed; Utilize smallest feasible vehicles; Engine preventive maintenance; Truck route planning

interests, disciplines, and skills" is still very true today, particularly in view of increased interest in UGM within DOT (7).

Current DOT Thrust in DPM

This interest is shared by former U.S. Secretary of Transportation Neil Goldschmidt who recently announced that:

> All regional transportation planning in the country must include a component which addresses goods movement and specifically the link between rail and highways, particularly in port communities.

A joint memorandum from the Federal Highway Administrator and Urban Mass Transportation Administrator further clarifies the Secretary's comments by stating that, in the past, certain issues have been overlooked in the planning process, including, "conflicts between freight and passenger movements; intercity truck movements in urban areas; service vehicle needs; congestion created by curb-side loading and unloading; access to ports, terminals, and other major activity centers by freight and public transportation modes; and resulting environmental, energy, and land use impacts." Further, the memorandum requests that key parties

be brought together to identify urban freight issues and existing and potential problems regarding short-range, TSM types of actions, long-range planning activities in the urban region, and site-specific modal transfer points. The most immediate concern will be with regard to the TSM actions, since they can be responded to most quickly and since they provide the most immediate potential for meaningful and measureable results.

UGM Actions in TSM Efforts

As has been suggested above, there is universal agreement that UGM problems are very local in nature; at the very least, they are manifested in localized conditions or impact. It might well be argued that the basic problems are quite universal and somewhat predictable. In fact, in examining the broad scope of

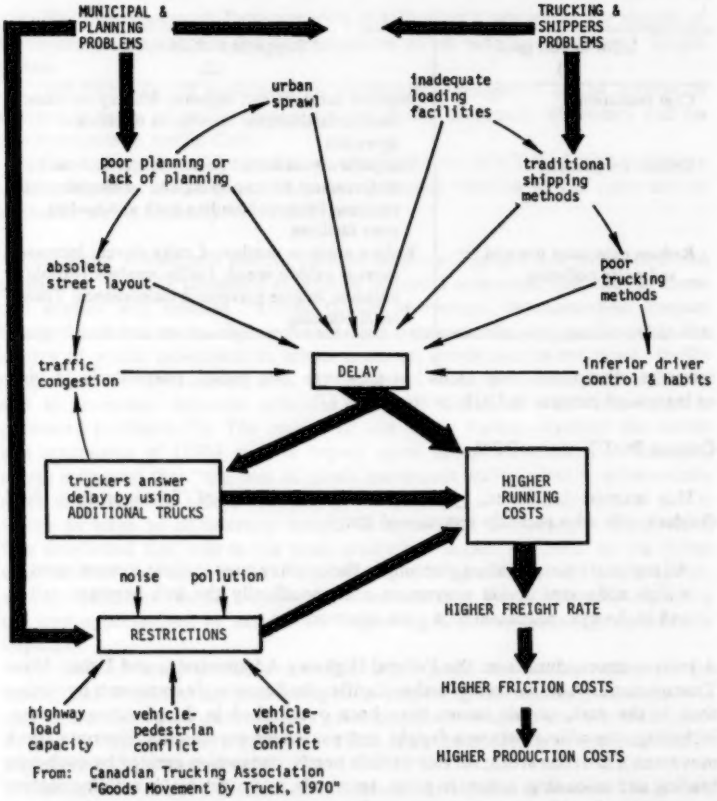

FIG. 1.—Representation of the UGM Problem

TABLE 3.—Problems and By-products of Urban Goods Distribution (3)

Problems of urban goods distribution (1)	By-Products: Congestion (2)	Pollution (3)	Safety (4)	Energy (5)	Higher operating costs passed on to consumer (6)	Economic development (7)
(*a*) Physical Characteristics of the Transportation System at the Shipping/Receiving Point						
Inadequate off-street loading/unloading facilities	X		X		X	
Inadequate design and access to off-street loading/unloading facilities	X			X	X	
Obstacles blocking access to off-street facilities	X			X	X	
Inadequate on-street loading/unloading facilities	X				X	
Physical obstacles to loading/unloading					X	
(*b*) Physical Characteristics of the Transportation System En Route to the Shipping/Receiving Point						
Network configuration	X	X		X	X	X
Street capacity	X	X		X	X	X
Facility design	X	X	X	X	X	X
Traffic control	X		X		X	
Major barriers to truck movements	X	X		X	X	X
Overhead and ground obstacles to truck movements			X	X	X	
(*c*) Policies of Governmental Agencies						
Lack of enforcement of loading zone restrictions	X	X		X	X	
Taxation and licensing	X	X		X	X	
Land use planning	X	X		X	X	X
Institutional jurisdictions between government agencies	X	X		X	X	X
(*d*) Business Operating Policies						
Limitations on the use of receiving facilities	X	X		X	X	
Lack of specialized equipment for freight handling and transportation					X	
Use of the driver-salesman for delivery	X	X		X	X	
Undesirable carrier response to insufficient receiving facilities	X	X		X	X	
Other pickup and delivery problems faced by carriers					X	

TABLE 3.—*Continued*

(1)	(2)	(3)	(4)	(5)	(6)	(7)
(*e*) Increase in the Total Number of Vehicles Moving Freight						
Increase in the volume of freight moved	X	X		X		
Increase in the number of small shipments	X	X		X	X	
Increase in the use of private carriage	X	X	X	X	X	
Increase in the dispersion of economic development		X		X	X	

UGM problems, congestion is predominant as the major impact. Congestion, however, is but one element of a system of problems associated with goods movement; in aggregate, the system has been represented quite accurately in an early Canadian UGM study and depicted in Fig. 1 (2).

A recent study of UGM problems and opportunities focused on short-range, low-cost TSM improvements for UGM. The study examined the UGM situation in six urban areas, both small and medium (3). The problem areas/opportunities, categorized in five groups, are presented in Table 3. The authors emphasized that these findings were applicable primarily to the cities under study and that UGM problems tend to be somewhat localized. However, it could be suggested that traffic signalization problems are also localized, but that there are certain underlying principles of design and operation which enable an engineer to study a specific local problem, ask the appropriate questions, collect the necessary data, and devise an acceptable solution. The real challenge of UGM research is to identify these underlying principles of operation and behavior.

A study conducted as part of DOT's University Research Program examined the facilitation of UGM in the Central Business District (CBD) area of Brooklyn, New York (5). The objective of the research was "the identification and formulation of the character of UGM and the development of a methodology for its improvement as one element of overall mobility." In particular, the study investigated the time and space requirements for pickup and delivery and service vehicles as a function of selected CBD land uses.

Within the somewhat specialized context studied, the general actions which were suggested as alternates for reducing the adverse impact of UGM in the downtown area include the following: (1) Temporal separation of goods and people movements; (2) spatial separation of goods and people movement; (3) consolidation terminals; and (4) curb and loading dock management. More specific suggestions regarding determination of space requirements, loading zone requirements, and dock sizing were also presented.

The New York Garment Center Study provides a useful contrast to the two aforementioned studies in that the area under study is one of highly specialized activity; nevertheless, the problems (and potential solutions) which were identified occur to some degree throughout the New York City metropolitan area (including Brooklyn) and in other urban areas as well. This study examined a number of possible solutions to extreme congestion and delays which, exempting those actions which relate directly to the peculiarities of the garment center, could

be applied in any number of urban areas (8). The short-term actions or improvements which were examined include the following:

1. Passenger vehicle ban.
2. Creation of turn lanes.
3. Restrictions on pedestrian crossings.
4. Reduction of truck parking durations.
5. Corner curb cuts.
6. Mid-block curb cuts.
7. Off-hour pickup and delivery (PUD).
8. Street widening.
9. Overnight off-street parking.
10. Standing/parking prohibitions on one curb lane.
11. Parking reservation system.

These improvements include many suggested actions which could be applied in Anytown, U.S.A., depending upon the problems encountered.

It can be seen, then, that there does exist a basis for the TSM planner from which to identify UGM problem situations and to suggest useful solutions. With regard to automobile traffic the local planner is conscious of the aim to reduce auto travel, in particular with trip ends in the CBD. There is, therefore, a concerted effort to promote disincentives for personal auto use, to encourage carpools, trip-chaining, and the like; at the same time, moreover, parallel efforts are underway to provide alternative transportation supply, such as transit and para-transit, to establish carpool matching programs, etc. With regard to TSM actions affecting UGM, efforts might be aimed at reducing congestion, delays, etc., but there has yet to be developed a set of alternatives to truck movement. Consequently, the TSM planner must move cautiously with regard to UGM actions so that he does not simply create barriers and restrictions to UGM vehicle movements.

Planning for UGM Improvements within the TSM Process

In spite of the accomplishments which are described above, a number of major hurdles still exist for the TSM planner. One primary difficulty is that there is no well-defined process whereby problem situations can be identified and traced to their root causes in such a way that appropriate feasible solution alternatives can be identified and evaluated in terms of the impacts created by their implementation (9). Such a process would take account of the many actors involved in UGM, and the requirements of and impacts upon each if hoped-for improvements can be realized. It would also help planners order and array their thinking about UGM problems so that local problems (and the potential solutions) can be looked upon in a generalized fashion. This would establish a common framework for identification of problems and definition of solutions.

In addition, there is a wide spectrum of issues which will need to be resolved if UGM ever will become a significant element within either the TSM or the urban transportation planning (UTP) process. One fundamental issue has been pointed out by Jones in his study of metropolitan transportation planning and

programming and the implications on TSM planning; he argues that the TSM regulations call for a TSM planning effort based on the traditional goal-achievement approach to long-range transportation planning embodied in the UTP process (10). The application of this approach to short-range TSM efforts is inappropriate because it emphasizes activities which are not necessary for implementation. Further, Jones points out that the success of TSM implementation is more closely related to the solution of a unique problem or the capture of a unique opportunity than to long-range policy planning. This is an important conclusion, particularly in view of the list identifying characteristics of successful TSM projects which he prepared. The list includes the following:

1. Projects have been limited in scale, scoped to a manageable political environment. They have often been initiated with the assistance and support of general purpose government.
2. They have generally involved the pursuit of limited, operational goals such as ameliorating specific design deficiencies or achieving savings in travel time.
3. Project implementation has improved the quality of service available without substantially disadvantaging any class of users or political jurisdiction.
4. Project managers have approached implementation with a demonstration philosophy and a readiness to abort or adjust design strategies as problems arise.
5. Project design has been negotiated with affected jurisdictions and interests—a time-consuming process involving intensive liaison and marketing efforts.
6. Project motivation has frequently been provided by the ability to capture federal funds in excess of formula entitlements.
7. The projects team has controlled resources which allowed them to make sidepayments of off-set adverse impacts (these sidepayments have typically been of the log-rolling variety; tree planting and beautification have been used to convince merchants to accept buslanes on commercial streets; states have financed the cost of resetting signals on local streets where ramp metering has been introduced).

These characteristics emphasize the short-term nature of successful TSM projects and the reliance on negotiated approaches. It should be noted that TSM measures related to UGM will require the involvement of the private sector (principally shippers and receivers) which, heretofore, was not needed in the TSM process. This will be an interesting and complex challenge for the TSM staff.

Remak (12) has also described some general rules or suggestions for identifying potential successful TSM improvements. These suggestions are summarized as follows:

1. Activities that improve the carrying capacity of existing roads—left-turn lanes, synchronized traffic signals, elimination of on-street parking—encourage the use of private automobiles and attract new users to the improved route.
2. Packages of TSM activities that work toward reducing demand for transportation resources, either at peak commuting times or generally, appear to have longer lasting and broader benefits than those that work toward increasing the

capacity of the transportation system. Such activities serve the combined objectives of reducing air pollution, automotive fuel consumption, and traffic congestion, and may also provide for greater mobility for those without access to cars.

3. Packages of TSM activities that attempt to increase vehicle occupancy must be directed toward areas, routes, and times for which there is a sufficient demand to provide the necessary level of ridership.

4. Where mobility for private automobiles is to be reduced by parking restraints, road pricing, or restricting entry to certain areas or reserved lanes, sufficient alternative modes of transportation must be immediately available. Packages of TSM activities using such penalties and restrictions must include other actions related to providing alternative transportation supply.

Remak has also pointed out that TSM planners "must rely largely on their professional experience and knowledge of their communities." This is undeniably true but it is interesting to note that in the TSM-related materials very little has been said about the problems of UGM in general, of integrating UGM into the TSM process, and of dealing with the UGM community. It would appear that the local planner will need a great deal more assistance and guidance if UGM is to be effectively integrated into the TSM element.

Talmers and Meyer (13) have made a useful suggestion regarding a framework for better understanding of urban freight movement, a framework which although it does not provide immediate assistance to the TSM planner currently involved with UGM problems, does provide a basis for study and analysis of the nature, magnitude, and characteristics of UGM with particular reference to the land use interactions which, in fact, stimulate the demand for goods movements. More thorough analyses of this type would be useful to the urban planner and to the TSM planner as well, particularly if they can be directed toward the root causes of UGM-related problems and the identification of solution alternatives.

The issue of how to integrate UGM into TSM planning appears to be the major need of this time, particularly in view of what has been accomplished in previous studies and in view of the Federal mandate to move in this direction. It is interesting to note that there appear to be two major directions that can be taken with regard to UGM, in general, and UGM within the TSM element, in particular. The TSM actions can be designed in response to individual symptoms or problems and then the TSM planner can proceed to "sell" his solution to the affected UGM community with the ensuing compromises and trade-offs before action can be taken. The necessary compromising in this approach to decision making can play havoc with the systematic logic of the original decision, particularly in view of the need to involve the private sector after an approach to controlling it is assumed.

An alternative approach would require a more careful and precise definition of the overall problem at hand and then a methodical review of every available course of action. This approach is time-consuming but it helps those involved and impacted to reach concensus within the decision-making process and to know what the decision is, what it means, and what is necessary to make it work. It can be argued that the second approach, which is based on Drucker's assessment of business decision making, is the appropriate one for UGM planning,

particularly since local MPO experience in working with UGM problems and with the UGM actors is extremely limited, in most instances (5).

The imposition of the TSM regulations taken together with the recent pronouncements regarding UGM considerations in future TSM plans suggest that UMTA and FHWA are in a position to provide assistance and guidance to the local MPOs regarding TSM planning. Previous discussions in this paper argue that, in spite of the significant work that has been accomplished, UMTA/FHWA has little to offer to the local MPOs regarding, in particular, the successful integration of UGM in the TSM planning process. The future success of UGM/TSM actions will depend quite heavily upon how quickly and how effectively UMTA/FHWA can meet the challenge of providing this necessary assistance.

Emerging Developments of 1980s

The previous section was primarily directed toward the more immediate problems of integrating UGM solutions into the TSM planning process as well. At this juncture, however, it is interesting to examine some of the more likely developments which will impact UGM operations in the future. There is considerable potential in the 1980s for changes in UGM operations both because of the constraints imposed on any system currently reliant upon petroleum-based energy and because of new directions in technological developments. There is no crystal ball one can query relative to what will happen, but recent and continuing developments point to some trends which might impact upon the UGM industry. These include the following:

1. Intermodal facility planning: A gradual rationalization of transportation facility planning and the organization of various modes within dedicated central facilities, which could stimulate improved organization of operations, including UGM.
2. Containerization and standardized shipping units: A move to support more mechanized warehousing and loading/unloading operations in an effort to reduce labor costs and improve efficiency.
3. Improved security: More comprehensive security programs to reduce losses due to theft, etc., which increase costs.
4. Hazardous materials: Increasing restrictions on the movement of any hazardous materials moving within metropolitan areas.
5. Alternative power sources: Use of electric and hybrid vehicles within urban areas to reduce petroleum consumption and pollution effects.
6. Improved planning models: Fulfilling a need for more accurate forecasts of UGM demand and UGM vehicle movements to accompany forecasts of other vehicle and person movements in the urban transportation planning process.
7. Improved ordering, billing, and routing systems: Centralized computer inventory systems which can aid the ordering and billing operation and which can be used in conjunction with algorithms to formulate efficient truck routing schemes.
8. Land use and UGM: In 1970 it was pointed out that freight transportation is a major user of urban land and that research was needed to explore questions regarding the most efficient use of land for freight transportation (6). This need

still exists, in particular relative to the relocation of freight facilities to improve their efficiency and thus to reclaim valuable land for redevelopment.

Final Comment

The author hopes that this paper provides some basis for further analysis regarding TSM planning and the inclusion of a heretofore neglected component, UGM, and provokes some response from both the UGM community and the TSM community. There is undoubtedly much to be done if UGM planning efforts are going to be successful and to assure that this opportunity is not squandered.

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Asymmetric Bending of Polar Orthotropic Circular Plates

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(Reviewed by the Aerospace Division)

Introduction

The static analysis of plates using the finite element method has been well documented (9,12). Within the scope of plate bending finite elements of various shapes have found application; among the most popular being rectangular (2), quadrilateral (3), and triangular elements (4). For problems involving curved boundaries, the triangular, quadrilateral, circular, and annular sector (7) finite elements have found application. The stiffness matrices for the circular and annular elements presented in Ref. 7 were derived using Hermitian interpolation polynomials as displacement functions with the translation and two rotations at a typical node being the displacement quantities of interest. Thus the model is basically two dimensional.

For the degenerate case of asymmetric bending of an isotropic circular plate a one-dimensional finite element model consisting of circular and annular elements has been presented (8). The forte of this particular work is that the displacement function used to determine the stiffness coefficients (all coefficients are presented in compact, algebraic expressions) identically satisfies the homogeneous circular plate bending differential equation. For those problems involving discrete axisymmetric nodal or equivalent nodal loads, this one-dimensional finite element model yields the exact results (10). Thus for the asymmetric bending of circular plates, an attractive alternative to the two-dimensional model such as presented in Ref. 7, is a solution strategy using a one-dimensional finite element model and a Fourier series approach to modeling the problem asymmetries. The use of semi-analytical techniques to reduce the complexity of the finite element model has been popular for quite some time—some of the early finite element models that used Fourier series to model the problem asymmetries included an axisymmetric conical shell (5) and an axisymmetric solid element. The bending of a circular plate was handled in Ref. 5 as a special case of the axisymmetric

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on May 6, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0301/$01.00.

conical shell. There the annular plate bending elements were treated as a degenerate case ($\phi - 90°$) of the conical shell elements. The displacement function employed for the asymmetric plate bending was the combination of Hermitian polynomials accounting for the radial behavior and Fourier terms reflecting the circumferential behavior. The present work is similar to that presented in Ref. 8 in that considerable effort has been spent in choosing the displacement function and formulating the resulting finite element model.

The rationale for investigating the asymmetric bending of circular plates by constructing a one-dimensional finite element model with a Fourier series representing problem asymmetries is threefold. First, it has been shown that the success of the finite element approach hinges on the choice of the assumed displacement pattern. In general the assumed displacement pattern should be chosen such that the true displacement is closely represented by the assumed displacement. The assumed displacement function that is the basis of this paper is more than just an approximation—in fact the displacement function identically satisfies the governing homogeneous, fourth-order, differential equation for the

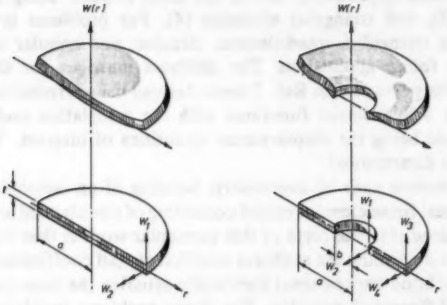

FIG. 1.—Circular and Annular Elements before and after Deformation

asymmetric bending of circular plates. Heuristically this is appealing. To start with the displacement function that identically satisfies the governing differential equation will provide the exact results (10) and these require a minimum number of elements to represent a given problem.

The second advantage for investigating the asymmetric circular plate problem is computer solution economy. A conventional solution strategy for the asymmetric bending problem is to discretize the circular plate continuum into an assemblage of circular and annular plate sectors with three degrees freedom per node. Thus the coarseness or fineness of the model is dictated by the number of elements (and hence nodes) representing the continuum. However, an economically attractive alternative to the aforementioned modeling technique is to present a basically one-dimensional model in the radial direction and assume the problem asymmetries can be expressed in Fourier series form. More precisely the circular plate model is an assemblage of complete annular rings (and possibly one circular element) with two nodal circular degrees-of-freedom at the boundary of adjoining elements (see Fig. 1). The asymmetries are accounted for by allowing

the nodal circular degrees-of-freedom (and thus bending moments, shears, etc.) to vary circumferentially. The total number degrees-of-freedom for a given problem is dictated by the product of the nodal circular displacements (two per nodal circle) and the number of terms retained in the Fourier series expansion. The economy of this solution strategy compared to the previously mentioned approach, is realized in two ways. First, since the physical model is basically a series of annular rings only a minimum of data is needed (and hence less error prone) to represent a given problem. Second, a bandwidth of such an approach is small—six—(coupling between two degrees-of-freedom of three consecutive nodes) regardless of how many terms of the Fourier series are retained. From a computing standpoint this is attractive—an efficient Gaussian elimination scheme can rapidly solve the problem involving a thousand simultaneous equations (which would be more than sufficient to represent most problems) because of the relative narrow bandwidth. In comparison, a two-dimensional model requiring a thousand unknowns has a bandwidth greatly in excess of six, and in general, depends on the number of nodes in a radial direction.

The third advantage of investigating the asymmetric bending of circular plates is to provide the designer and the analyst a relatively inexpensive means of attacking such problems. Using classical techniques, such as solving the differential equation and employing boundary conditions, proves to be quite tedious and highly prone to error. Most problems in fact are intractable using classical techniques due to the complexity of the governing equations.

Displacement Function

The classical equilibrium equation of an unloaded annular plate possessing cylindrical orthotropy subject to asymmetric translation and rotation boundary displacements is (12)

$$D_r w'''' + \frac{2D_{r\theta}\ddot{w}''}{r^2} + \frac{D_\theta \ddot{w}}{r^4} + \frac{2D_r w'''}{r} - \frac{2D_{r\theta}\ddot{w}'}{r^3} - \frac{D_\theta w''}{r^2} + \frac{2(D_\theta + D_{r\theta})\ddot{w}}{r^4} + \frac{D_\theta w'}{r^3} = q(r,\theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Assuming the asymmetric translations at the inner and outer radii can be expressed in Fourier form such as (see Fig. 2)

$$w(b,\theta) = \sum_{n=0}^{\infty} w_{1n} \cos n\theta, \quad w(a,\theta) = \sum_{n=0}^{\infty} w_{3n} \cos n\theta$$

$$w'(b,\theta) = \sum_{n=0}^{\infty} w_{2n} \cos n\theta, \quad w'(a,\theta) = \sum_{n=0}^{\infty} \cos n\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

(the extension to include the sine terms is simple in concept), then the solution to Eq. 1 subject to the aforementioned boundary conditions can be expressed as

$$w(r,\theta) = \sum_{n=0}^{\infty} F_n(r)\, G_n(\theta) = \sum_{n=0}^{\infty} [\phi_{1n}(r)\, w_{1n} + \phi_{2n}(r)\, w_{2n} + \phi_{3n}(r)\, w_{3n}$$

$$+ \phi_{4n}(r)\, w_{4n}] \cos n\theta \quad \ldots\ldots\ldots\

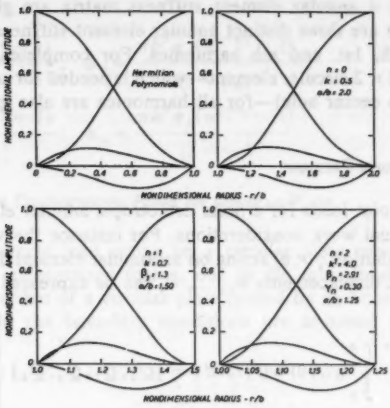

FIG. 3.—Comparison of Orthotropic Shape Functions and Hermition Polynomials

to the Hermitian interpolation polynomials of order 4. Graphs of these shape functions for typical values of harmonic n and moduli ratio are compared with the Hermitian interpolation polynomials of order 4 in Fig. 3. Note the relative invariance of the shape functions with harmonic and moduli ratio.

Stiffness Matrix—Circular and Annular Elements

The strain energy of an annular plate due to bending and twisting can be expressed in polar coordinate form as

$$U = \frac{1}{2}\int_0^{2\pi}\int_b^a D_r\left[(w'')^2 + k^2\left(\frac{w'}{r} + \frac{\ddot{w}}{r^2}\right)^2 + 2w''\left(\frac{w'}{r} + \frac{\ddot{w}}{r^2}\right)^2 + 2j^2\left(\frac{\dot{w}'}{r} - \frac{\dot{w}}{r^2}\right)^2\right] r dr d\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

in which primes denote derivatives with respect to the radial coordinate r whereas dots denote derivatives with respect to the circumferential coordinate θ. By substituting the assumed displacement patterns given in Eq. 3 into Eq. 5 and performing the indicated differentiations and integrations, the strain energy can be expressed in matrix quadratic form as

$$U = \frac{1}{2}\sum_{n=0}^{\infty} \mathbf{W}_n^T \mathbf{K}_n \mathbf{W}_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The 4×1 displacement vector has the form

$$\mathbf{W}_n^T = \{w_{1n}\ w_{2n}\ w_{3n}\ w_{4n}\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

in which the first subscript of a typical Fourier coefficient denotes the displacement type; and the second subscript denotes the harmonic. The coefficients

for a typical 4 × 4 annular element stiffness matrix are given in Appendix II. Note that there are three distinct annular element stiffness matrices corresponding to the 0th, 1st, and nth harmonics. For completeness, the stiffness coefficients for a 2 × 2 circular element—which is needed for analyzing complete circular plates (no center hole)—for all harmonics are also given in Appendix II.

Load Vector—Uniform Pressure

The equivalent joint loads for a polar orthotropic annular element are readily obtained from virtual work considerations. For instance the virtual work done by a pressure distribution $q(r, \theta)$ acting on an annular element due to an arbitrary set of virtual nodal displacements $w_1, \ldots, w_4$ can be expressed as

$$\text{virtual work} = \int_0^{2\pi} \int_b^a q(r, \theta)\, w(r)\, r dr d\theta = [Q_1, Q_2, Q_3, Q_4] \begin{Bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{Bmatrix} \quad \ldots . \quad (8)$$

in which generalized forces $Q_1, \ldots, Q_4$ can be thought of as equivalent joint loads replacing the pressure distribution $q(r, \theta)$. Substituting the displacement function $w(r)$ given in Eq. 3 into the foregoing expression gives the ith equivalent joint load as

$$Q_i = \sum_{j=1}^{4} \gamma_{ij} \psi_j \quad \ldots \quad (9)$$

The coefficients γ_{ij} are the same shape function coefficients given in Appendix I and the coefficients ψ_j depend upon the form of the distributed loading $q(r, \theta)$. For instance, the coefficients ψ_j corresponding to a distributed load that is radially invariant but whose circumferential variation can be expressed as

$$q(r, \theta) = \sum_{n=0}^{\infty} q_n \cos n\theta$$

leads to the following expressions.

For $n = 0$:

$$\psi_1 = \pi b^2 q_0 (\alpha^2 - 1); \quad \psi_2 = \frac{\pi b^2 q_0 (\alpha^4 - 1)}{2};$$

$$\psi_3 = \frac{2\pi b^2 q_0 (\alpha^{3+k} - 1)}{(3 + k)}; \quad \psi_4 = \frac{2\pi b^2 q_0 (\alpha^{3-k} - 1)}{(3 - k)} \quad \ldots \quad (10)$$

For $n = 1$:

$$\psi_1 = \frac{\pi b^2 q_1 (\alpha^3 - 1)}{3}; \quad \psi_2 = \frac{\pi b^2 q_1 (\alpha^{3-\beta_1} - 1)}{(3 - \beta_1)};$$

$$\psi_3 = \frac{\pi b^2 q_1 (\alpha^{3+\beta_1} - 1)}{(3 + \beta_1)}; \quad \psi_4 = \frac{\pi b^2 q_1 [\alpha^3 (\log \alpha - 1) + 1]}{9} \quad \ldots \quad (11)$$

For $n > 1$:

$$\psi_1 = \frac{\pi b^2 q_n(\alpha^{3+\gamma_n} - 1)}{(3 + \gamma_n)}; \quad \psi_2 = \frac{\pi b^2 q_n(\alpha^{3-\beta_n} - 1)}{(3 - \beta_n)};$$

$$\psi_3 = \frac{\pi b^2 q_n(\alpha^{3+\beta_n} - 1)}{(3 + \beta_n)}; \quad \psi_4 = \frac{\pi b^2 q_n(\alpha^{3-\gamma_n} - 1)}{(3 - \gamma_n)} \quad \ldots\ldots\ldots\ldots (12)$$

Example—Eccentric Concentrated Force on Circular Plate

Since any transverse load acting on a circular plate can be replaced by a finite number of concentrated forces, one of the most fundamental problems in plate bending is that of a circular plate loaded by an eccentric concentrated force. Even when the boundary conditions are assumed to be rotationally

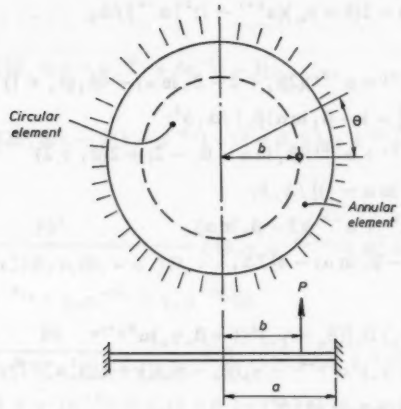

FIG. 4.—Clamped Circular Plate with Concentrated Load

symmetric, the analysis due to such asymmetric loads using classical techniques is quite tedious and highly prone to error. However a finite element analysis frees the analyst of such tedium by readily obtaining the deformations and internal forces.

Consider, for example the plate shown in Fig. 4 to be clamped around the perimeter. Using a finite element model consisting of one circular and one annular element, the problem reduces to finding the $2n$ displacements corresponding to the translation w_{1n} and radial slope w_{2n} at $r = b$ for n harmonics. The problem can be represented by the matrix equation

$$\mathbf{KW} = \mathbf{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

in which stiffness matrix $\mathbf{K}$ is of order $2n \times 2n$; and displacement $\mathbf{W}$ and load $\mathbf{P}$ vectors are both of order $2n \times 1$. However, due to orthogonality conditions, the n harmonics are all uncoupled so that the problem posed in the equation

can be equally represented by n two degrees-of-freedom problems such as

$$\sum_{n=0}^{\infty} (\mathbf{K}_n \mathbf{W}_n = \mathbf{P}_n) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (14)$$

The 2×2 matrices $\mathbf{K}_n$ in the above equation are obtained by combining the appropriate stiffness coefficients for the circular and annular elements given in Appendix II.

For $n = 0$:

$$K_{11} = 4\pi D_r (k^2 - 1)^2 (\alpha^k - \alpha^{-k}) / b^2 \Delta_0;$$

$$K_{12} = 4\pi D_r (k^2 - 1)[2k\alpha(\alpha^{-k-1} - 1) + (k+1)(\alpha^k - \alpha^{-k})] / b\Delta_0;$$

$$K_{22} = 2\pi D_r \{(\alpha^k - \alpha^{-k})[2(k^2 + \nu_{\theta r})(k+1)(\alpha^2 - 1) + 2(k+1)(1+\nu_{\theta r})$$
$$- 2(k - \nu_{\theta r})(k-1)\alpha^2] - 8k(1+\nu_{\theta r})\alpha + 2k[2(1+\nu_{\theta r})(\alpha^2 + 1)$$
$$+ (k^2 - 1)(\alpha^2 - 1) - 2(k + \nu_{\theta r})(\alpha^{k+1} - 1)^2]\alpha^{-k}\} / \Delta_0 \quad \ldots \ldots \ldots \quad (15)$$

For $n = 1$:

$$K_{11} = \pi\alpha\beta_1^2 D_r [(\alpha^{\beta_1} + \alpha^{-\beta_1})(2\beta_1 + 2 - \beta_1 \ln\alpha) - 4\beta_1(\beta_1 + 1)$$
$$- (\alpha^{\beta_1} - \alpha^{-\beta_1})(\beta_1^2 - 1 + \beta_1 \ln\alpha)\beta_1] / \Delta_1 b^2;$$

$$K_{21} = \pi\alpha\beta_1^2 D_r [(\alpha^{\beta_1} + \alpha^{-\beta_1})(\beta_1 \ln\alpha - \beta_1 - 2) + 2(\beta_1 + 2)$$
$$+ (\alpha^{\beta_1} - \alpha^{-\beta_1})(\beta_1 \ln\alpha - 1)] / \Delta_1 b;$$

$$K_{22} = \pi\alpha\beta_1^2 D_r [(\alpha^{\beta_1} + \alpha^{-\beta_1})(2 - \beta_1 \ln\alpha)$$
$$+ (\alpha^{\beta_1} - \alpha^{-\beta_1})(1 - \beta_1 \ln\alpha) - 4] / \Delta_1 \quad \ldots \ldots \ldots \ldots \ldots \quad (16)$$

For $n > 1$:

$$K_{11} = 2\pi\alpha(\beta_n - \gamma_n) D_r [(\beta_n - \gamma_n)^2 (1 + \beta_n\gamma_n)\alpha^{\beta_n + \gamma_n}$$
$$- \beta_n(\beta_n - \gamma_n)(1 + \gamma_n)^2 \alpha^{\beta_n + \gamma_n} - \gamma_n(\beta_n + \gamma_n)(1 + \beta_n)^2 \alpha^{\gamma_n - \beta_n}$$
$$+ 4\beta_n\gamma_n(1 + \beta_n)(1 + \gamma_n)] / \Delta_n b^2;$$

$$K_{21} = 2\pi\alpha(\beta_n + \gamma_n) D_r [\beta_n(1 + \gamma_n)(\beta_n + \gamma_n)\alpha^{\beta_n - \gamma_n}$$
$$+ \gamma_n(1 + \beta_n)(\beta_n + \gamma_n)\alpha^{\gamma_n - \beta_n} - (\beta_n - \gamma_n)^2 \alpha^{\beta_n + \gamma_n} - 2\beta_n\gamma_n(\beta_n + \gamma_n$$
$$+ 2)] / \Delta_n b; \quad K_{22} = 2\pi\alpha(\beta_n + \gamma_n) D_r [(\beta_n - \gamma_n)^2 \alpha^{\beta_n + \gamma_n}$$
$$- \beta_n(\beta_n + \gamma_n)\alpha^{\beta_n + \gamma_n} - \gamma_n(\beta_n + \gamma_n)\alpha^{\gamma_n - \beta_n} - 4\beta_n\gamma_n] / \Delta_n \quad \ldots \ldots \ldots \quad (17)$$

The contribution to the load vector can be found by considering the virtual work done by the concentrated force P in cosine Fourier series form as (12)

$$P^*(b, \theta) = \frac{P}{\pi b}\left(\frac{1}{2} + \sum_{m=1}^{\infty} \cos m\theta\right) \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (18)$$

and then expressing the virtual work as

$$V = \int_0^{2\pi} P^*(b, \theta)\, w(b, \theta)\, b\, d\theta;$$

$$V = \int_0^{2\pi} \frac{P}{\pi b}\left(\frac{1}{2} + \sum_{m=1}^{\infty} \cos m\theta\right)\left(W_{10} + \sum_{n=1}^{\infty} W_{1n} \cos n\theta\right) \quad \ldots\ldots\ldots (19)$$

Performing the above integrations give the load vector $\mathbf{P}_n$ for all harmonics as

$$\mathbf{P}_n^T = \{P, 0\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Knowing the stiffness and load vector coefficients for all harmonics, the displacement coefficients can be determined from Eq. 13.

For $n = 0$;

$$W_{10} = \frac{Pb^2}{4\pi k(k+1)(k^2-1)D_r}[4k\alpha^{1-k} - (k-1)\alpha^{-2k} + \alpha^2 k(k-1) - (k+1)^2],$$

$$W_{20} = \frac{Pb}{4\pi k(k^2-1)D_r}[2k\alpha^{1-k} - (k-1)\alpha^{-2k} - (k+1)] \quad \ldots\ldots\ldots (21)$$

For $n = 1$:

$$W_{11} = \frac{Pb^2}{2\pi\beta_1^3 D_r}[2\beta_1 \ln\alpha - \alpha^{-2\beta_1} + 4\alpha^{-\beta_1} - 3];$$

$$W_{21} = \frac{Pb}{2\pi\beta_1^3 D_r}[2\beta_1 \ln\alpha - 2(1-\alpha^{-\beta_1}) - (1+\beta_1)(1-\alpha^{-\beta_1})^2] \quad \ldots\ldots (22)$$

For $n > 1$:

$$W_{1n} = \frac{Pb^2}{2\pi(\beta_n^2 - \gamma_n^2)\beta_n\gamma_n(\beta_n - \gamma_n)D_r}\{4\beta_n\gamma_n\alpha^{-\beta_n-\gamma_n} + \beta_n^2 + \gamma_n^2$$
$$- (\beta_n + \gamma_n)(\beta_n\alpha^{-2\gamma_n} + \gamma_n\alpha^{-2\gamma_n} + \gamma_n\alpha^{-2\beta_n})\};$$

$$W_{2n} = \frac{Pb}{2\pi(\beta_n^2 - \gamma_n^2)\beta_n\gamma_n(\beta_n - \gamma_n)D_r}\{2\beta_n\gamma_n(2 + \beta_n + \gamma_n)\alpha^{-\beta_n-\gamma_n}$$
$$- (\beta_n + \gamma_n)[\beta_n(1+\gamma_n)\alpha^{-2\gamma_n} + \gamma_n(1+\beta_n)\alpha^{-2\beta_n}] + (\beta_n - \gamma_n)^2\} \quad \ldots\ldots (23)$$

The aforementioned displacement components are identical to those presented in Ref. 6. It should be noted that there are two typographical errors in Ref. 6, that were uncovered when documenting this example problem. The corrections to Ref. 6, pp. 378–379 are as follows:

1. Equation (82.19): The third term within the square brackets $R_n^1(r)$ should have a minus sign rather than a plus sign.
2. Equation (82.20): The third term within the square brackets for $R_1^2(r)$ should be multiplied by (r/b).

This example problem demonstrates the accuracy of the technique but, more importantly, emphasizes the tedious and cumbersome details associated with even the simplest of problems. In particular, if one were to analyze orthotropic circular plates on a continuing basis, then the only practical means to avoid the errors and tedium of the closed form solution would be to use a finite

element solution. For example, a thoroughly documented, exhaustively checked out computer code was developed as a result of this project and can be found in Ref. 1.

Conclusion

The circular and annular element stiffness matrices for the 0th, 1st, and nth harmonics are given in closed form. These stiffness coefficients, which are exact for a problem involving discrete nodal loads, can be readily coded into any structural analysis program using standard finite element techniques. The payoff in attacking asymmetric circular plate bending problems using the finite element method is that it frees the analyst or designer from the tedious and error-prone calculations associated with even the simplest problems.

Appendix I.

Shape Functions: Annular Element.—Each shape function $\phi_{in}(r)$ can be expressed as the summed product of a shape function coefficient γ_{ij} and a radial displacement pattern $\rho_j(r)$ for all values of n. Thus

$$\phi_{in}(r) = \sum_{j=1}^{4} \gamma_{ij}\rho_j(r) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (24)$$

For $n = 0$:

$$\rho_1(r) = 1, \quad \rho_2(r) = \left(\frac{r}{b}\right)^2, \quad \rho_3(r) = \left(\frac{r}{b}\right)^{1+k}, \quad \rho_4(r) = \left(\frac{r}{b}\right)^{1-k};$$

$$\gamma_{11} = [(k+1)^2\alpha^2(\alpha^k - \alpha^{-k}) - 4k\alpha(\alpha^{k+1} - 1)]/\Delta_0;$$

$$\gamma_{12} = (1-k^2)(\alpha^k - \alpha^{-k})/\Delta_0; \quad \gamma_{13} = -2(k-1)\alpha(\alpha^{-k-1} - 1)/\Delta_0;$$

$$\gamma_{14} = -2(k+1)\alpha(\alpha^{k-1} - 1)/\Delta_0; \quad \gamma_{21} = b[2k\alpha(\alpha^{k+1} - 1)$$

$$-(k+1)\alpha^2(\alpha^k - \alpha^{-k})]/\Delta_0; \quad \gamma_{22} = b[-(k+1)(\alpha^k - \alpha^{-k})$$

$$-2k\alpha(\alpha^{-k-1} - 1)]/\Delta_0; \quad \gamma_{23} = b[(k-1)\alpha^{-k}(1-\alpha^2) - 2\alpha(\alpha^{-k+1} - 1)]/\Delta_0;$$

$$\gamma_{24} = b[(k+1)\alpha^k(1-\alpha^2) + 2\alpha(\alpha^{k+1} - 1)]/\Delta_0;$$

$$\gamma_{31} = [-(k+1)^2(\alpha^k - \alpha^{-k}) - 4k\alpha(\alpha^{-k-1} - 1)]/\Delta_0; \quad \gamma_{32} = -\gamma_{12}\gamma_{33} = -\gamma_{13}$$

$$\gamma_{34} = -\gamma_{14}; \quad \gamma_{41} = b[(k+1)\alpha(\alpha^k - \alpha^{-k}) + 2k\alpha^2(\alpha^{-k-1} - 1)]/\Delta_0;$$

$$\gamma_{42} = b[(k+1)\alpha(\alpha^k - \alpha^{-k}) - 2k(\alpha^{k+1} - 1)]/\Delta_0;$$

$$\gamma_{43} = b[(k-1)(\alpha^2 - 1) + 2(\alpha^{-k+1} - 1)]/\Delta_0;$$

$$\gamma_{44} = b[(k+1)(\alpha^2 - 1) - 2(\alpha^{k+1} - 1)]/\Delta_0;$$

$$\Delta_0 = (k+1)^2(\alpha^k - \alpha^{-k})(\alpha^2 - 1) - 4k\alpha^{-k}(\alpha^{k+1} - 1)^2 \quad \ldots \ldots \ldots \quad (25)$$

For $n = 1$:

$$\rho_1(r) = \frac{r}{b}, \quad \rho_2(r) = \left(\frac{r}{b}\right)^{1-\beta_1}, \quad \rho_3(r) = \left(\frac{r}{b}\right)^{1+\beta_1}, \quad \rho_4(r) = \left(\frac{r}{b}\right)\ln\left(\frac{r}{b}\right);$$

$\gamma_{11} = \alpha\,[\beta_1^2 \ln\alpha\,(\alpha^{-\beta_1} - \alpha^{\beta_1}) + \beta_1(\alpha^{\beta_1} + \alpha^{-\beta_1} + \alpha^{\beta_1}\ln\alpha + \alpha^{-\beta_1}\ln\alpha - 2)$
$+ \alpha^{-\beta_1} - \alpha^{\beta_1}]/\Delta_1$; $\gamma_{12} = \alpha\,[\beta_1(\alpha^{\beta_1} - \alpha^{\beta_1}\ln\alpha - 1) + \alpha^{\beta_1} - 1]/\Delta_1$;
$\gamma_{13} = \alpha\,[\beta_1(\alpha^{-\beta_1} - \alpha^{-\beta_1}\ln\alpha - 1) - \alpha^{-\beta_1} + 1]/\Delta_1$; $\gamma_{14} = \alpha\beta_1\,[\beta_1(\alpha^{\beta_1} - \alpha^{-\beta_1})$
$- (\alpha^{\beta_1} + \alpha^{-\beta_1} - 2)]/\Delta_1$; $\gamma_{21} = b\alpha\,[-\beta_1\ln\alpha(\alpha^{\beta_1} + \alpha^{-\beta_1}) + \alpha^{\beta_1} - \alpha^{-\beta_1}]/\Delta_1$;
$\gamma_{22} = b\alpha(\beta_1\alpha^{\beta_1}\ln\alpha - \alpha^{\beta_1} + 1)/\Delta_1$; $\gamma_{23} = b\alpha(\beta_1\alpha^{-\beta_1}\ln\alpha + \alpha^{-\beta_1} - 1)/\Delta_1$;
$\gamma_{24} = b\alpha\beta_1(\alpha^{\beta_1} + \alpha^{-\beta_1} - 2)/\Delta_1$; $\gamma_{31} = [\beta_1(-2\ln\alpha + \alpha^{\beta_1} - \alpha^{-\beta_1})$
$+ \alpha^{\beta_1} - \alpha^{-\beta_1}]/\Delta_1$; $\gamma_{32} = [\beta_1(\ln\alpha - \alpha^{\beta_1} + 1) - \alpha^{\beta_1} + 1]/\Delta_1$;
$\gamma_{33} = [\beta_1(\ln\alpha - \alpha^{-\beta_1} - 1) + \alpha^{-\beta_1} - 1]/\Delta_1$; $\gamma_{34} = \beta_1\,[\beta_1(\alpha^{-\beta_1} - \alpha^{\beta_1})$
$- (\alpha^{\beta_1} + \alpha^{-\beta_1} - 2)]/\Delta_1$; $\gamma_{41} = b\alpha(\alpha^{-\beta_1} - \alpha^{\beta_1} + 2\beta_1\ln\alpha)/\Delta_1$;
$\gamma_{42} = b\alpha(\alpha^{\beta_1} - \beta_1\ln\alpha - 1)/\Delta_1$; $\gamma_{43} = b\alpha(-\alpha^{-\beta_1} - \beta_1\ln\alpha + 1)/\Delta_1$;
$\gamma_{44} = \gamma_{24}$; $\Delta_1 = \alpha\beta_1\,[\beta_1\ln\alpha(\alpha^{-\beta_1} - \alpha^{\beta_1}) + 2(\alpha^{\beta_1} + \alpha^{-\beta_1} - 2)]$;

$$\beta_1 = \sqrt{1 + k^2 + 2\nu_{\theta r} + 2j^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

For $n > 1$:

$$\rho_1(r) = \left(\frac{r}{b}\right)^{1+\gamma_n} \quad \rho_2(r) = \left(\frac{r}{b}\right)^{1-\beta_n} \quad \rho_3(r) = \left(\frac{r}{b}\right)^{1+\beta_n} \quad \rho_4(r) = \left(\frac{r}{b}\right)^{1-\gamma_n};$$

$\gamma_{11} = \alpha\,[(\beta_n + \gamma_n)(1 - \beta_n)\alpha^{-\gamma_n+\beta_n} + (\beta_n - \gamma_n)(1 + \beta_n)\alpha^{-\gamma_n-\beta_n} + 2\beta_n(\gamma_n$
$- 1)]/\Delta_n$; $\gamma_{12} = \alpha\,[(\gamma_n - \beta_n)(\gamma_n - 1)\alpha^{\beta_n+\gamma_n} - (\gamma_n + \beta_n)(1 + \gamma_n)\alpha^{\beta_n-\gamma_n}$
$+ 2\gamma_n(\beta_n + 1)]/\Delta_n$; $\gamma_{13} = \alpha\,[(\gamma_n + \beta_n)(1 - \gamma_n)\alpha^{-\beta_n+\gamma_n}$
$+ (\gamma_n - \beta_n)(1 + \gamma_n)\alpha^{-\beta_n-\gamma_n} + 2\gamma_n(\beta_n - 1)]/\Delta_n$;
$\gamma_{14} = \alpha\,[(\beta_n - \gamma_n)(\beta_n - 1)\alpha^{\gamma_n+\beta_n} - (\beta_n + \gamma_n)(1 + \beta_n)\alpha^{\gamma_n-\beta_n} + 2\beta_n(\gamma_n$
$+ 1)]/\Delta_n$; $\gamma_{21} = b\alpha\,[(-\beta_n - \gamma_n)\alpha^{\beta_n-\gamma_n} + (-\beta_n + \gamma_n)\alpha^{-\beta_n-\gamma_n} + 2\beta_n]/\Delta_n$;
$\gamma_{22} = b\alpha\,[(\gamma_n - \beta_n)\alpha^{\gamma_n+\beta_n} + (\gamma_n + \beta_n)\alpha^{-\gamma_n+\beta_n} - 2\gamma_n]/\Delta_n$;
$\gamma_{23} = b\alpha\,[(-\gamma_n - \beta_n)\alpha^{\gamma_n-\beta_n} + (-\gamma_n + \beta_n)\alpha^{-\gamma_n-\beta_n} + 2\gamma_n]/\Delta_n$;
$\gamma_{24} = b\alpha\,[(\beta_n - \gamma_n)\alpha^{\beta_n+\gamma_n} + (\beta_n + \gamma_n)\alpha^{-\beta_n+\gamma_n} - 2\beta_n]/\Delta_n$;
$\gamma_{31} = [(\beta_n + \gamma_n)(1 - \beta_n)\alpha^{-\beta_n} + (\beta_n - \gamma_n)(1 + \beta_n)\alpha^{\beta_n} + 2\beta_n(\gamma_n$
$- 1)\alpha^{-\gamma_n}]/\Delta_n$; $\gamma_{32} = [(\gamma_n - \beta_n)(\gamma_n - 1)\alpha^{-\gamma_n} - (\gamma_n + \beta_n)(1 + \gamma_n)\alpha^{\gamma_n}$
$+ 2\gamma_n(\beta_n + 1)\alpha^{\beta_n}]/\Delta_n$; $\gamma_{33} = [(\gamma_n + \beta_n)(1 - \gamma_n)\alpha^{-\gamma_n} + (\gamma_n - \beta_n)(1$
$+ \gamma_n)\alpha^{\gamma_n} + 2\gamma_n(\beta_n - 1)\alpha^{-\beta_n}]/\Delta_n$; $\gamma_{34} = [(\beta_n - \gamma_n)(\beta_n - 1)\alpha^{-\beta_n} - (\beta_n$
$+ \gamma_n)(1 + \beta_n)\alpha^{\beta_n} + 2\beta_n(\gamma_n + 1)\alpha^{\gamma_n}]/\Delta_n$; $\gamma_{41} = b\alpha\,[(-\beta_n - \gamma_n)\alpha^{-\beta_n}$
$+ (-\beta_n + \gamma_n)\alpha^{\beta_n} + 2\beta_n\alpha^{-\gamma_n}]/\Delta_n$;
$\gamma_{42} = b\alpha\,[(\gamma_n - \beta_n)\alpha^{-\gamma_n} + (\gamma_n + \beta_n)\alpha^{\gamma_n} - 2\gamma_n\alpha^{\beta_n}]/\Delta_n$;
$\gamma_{43} = b\alpha(-\gamma_n - \beta_n)\alpha^{-\gamma_n} + (-\gamma_n + \beta_n)\alpha^{\gamma_n} + 2\gamma_n\alpha^{-\beta_n}]/\Delta_n$;
$\gamma_{44} = b\alpha\,[(\beta_n - \gamma_n)\alpha^{-\beta_n} + (\beta_n + \gamma_n)\alpha^{\beta_n} - 2\beta_n\alpha^{\gamma_n}]/\Delta_n$;
$\Delta_n = \alpha\,[8\gamma_n\beta_n + (\gamma_n - \beta_n)^2(\alpha^{\gamma_n+\beta_n} + \alpha^{-\gamma_n-\beta_n}) - (\gamma_n + \beta_n)^2(\alpha^{-\gamma_n+\beta_n} + \alpha^{-\beta_n+\gamma_n})]$;

$$\beta_n = \sqrt{\frac{1}{2}(1 + k^2 + 2n^2\nu_{\theta r} + 2n^2 j^2) + \sqrt{\frac{1}{4}(1 + k^2 + 2n^2\nu_{\theta r} + 2n^2 j^2)^2 - k^2(n^2 - 1)^2}};$$

$$\gamma_n = \sqrt{\frac{1}{2}(1 + k^2 + 2n^2\nu_{\theta r} + 2n^2 j^2) - \sqrt{\frac{1}{4}(1 + k^2 + 2n^2\nu_{\theta r} + 2n^2 j^2)^2 - k^2(n^2 - 1)^2}} \quad (27)$$

Shape Functions: Circular Element.—For completeness a circular element with two degrees-of-freedom is needed for the analysis of a circular plate with no center hole. The displacement function for the circular element has special forms for $n = 0$, $n = 1$, and $n > 1$.

For $n = 0$:

$$w(r, \theta) = w_{10} + \left(\frac{a}{k+1}\right)\left[\left(\frac{r}{a}\right)^{k+1} - 1\right] w_{20} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

For $n = 1$:

$$w(r, \theta) = \left[(1 + \beta_1)\left(\frac{r}{a}\right) - \left(\frac{r}{a}\right)^{1+\beta_1}\right] \frac{w_{11} \cos\theta}{\beta_1}$$

$$+ \left[\left(\frac{r}{a}\right)^{1+\beta_1} - \left(\frac{r}{a}\right)\right] \frac{w_{21} \cos\theta}{\beta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

For $n > 1$:

$$w(r, \theta) = \left[(1 + \beta_n)\left(\frac{r}{a}\right)^{1+\gamma_n} - (1 + \gamma_n)\left(\frac{r}{a}\right)^{1+\beta_n}\right] \frac{w_{1n} \cos n\theta}{\beta_n - \gamma_n}$$

$$+ \left[\left(\frac{r}{a}\right)^{1+\beta_n} - \left(\frac{r}{a}\right)^{1+\gamma_n}\right] a \frac{w_{2n} \cos n\theta}{\beta_n - \gamma_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (30)$$

Appendix II.

Stiffness Matrices: Annular Element.—There are three 4×4 element stiffness matrices for a typical annular element corresponding to the 0th, 1st, and nth harmonics.

For $n = 0$:

$$K_{11} = 4\pi D_r(k^2 - 1)^2(\alpha^k - \alpha^{-k})/b^2\Delta_0; \quad K_{21} = 4\pi D_r(k^2 - 1)[2k\alpha(\alpha^{-k-1} - 1)$$

$$+ (k + 1)(\alpha^k - \alpha^{-k})]/b\Delta_0; \quad K_{31} = -K_{11};$$

$$K_{41} = 4\pi D_r(k^2 - 1)[2k(\alpha^{k+1} - 1) - (k + 1)\alpha(\alpha^k - \alpha^{-k})]/b\Delta_0;$$

$$K_{22} = 2\pi D_r\{(\alpha^k - \alpha^{-k})[(k - \nu_{\theta r})(k^2 - 1)(\alpha^2 - 1) - 2(k - \nu_{\theta r})(k - 1)\alpha^2$$

$$+ 2(k + 1)(1 + \nu_{\theta r})] - 8k(1 + \nu_{\theta r})\alpha - 2[k(k^2 - 1)(1 - \alpha^2)$$

$$- 2k(1 + \nu_{\theta r})(1 + \alpha^2)]\alpha^{-k}\}/\Delta_0; \quad K_{32} = -K_{21};$$

$$K_{42} = 4\pi D_r(k^2 - 1)[(\alpha^k - \alpha^{-k})\alpha - k(\alpha^2 - 1)]/\Delta_0; \quad K_{33} = K_{11};$$

$$K_{43} = -K_{41}; \quad K_{44} = 2\pi D_r\{(\alpha^k - \alpha^{-k})(k + 1)[2(1 + \nu_{\theta r})\alpha^2$$

$$+ (k + \nu_{\theta r})(k - 1)(\alpha^2 - 1) - 2(k + \nu_{\theta r})] + 2k\alpha^{-k}[(k^2 - 1)(\alpha^2 - 1)$$

$$- 2(1 + \nu_{\theta r})] - 4k(1 + \nu_{\theta r})\alpha(\alpha^{k+1} - 2)\}/\Delta_0;$$

$$\Delta_0 = (k + 1)^2(\alpha^k - \alpha^{-k})(\alpha^2 - 1) - 4k\alpha^{-k}(\alpha^{k+1} - 1)^2 \quad \ldots\ldots\ldots\ldots \quad (31)$$

For $n = 1$:

$$K_{11} = \pi\alpha\beta_1\{D_r[(\alpha^{\beta_1} + \alpha^{-\beta_1})(2\nu_{\theta r} - \beta_1^2 \ln\alpha) - 4\nu_{\theta r}$$
$$+ (\alpha^{\beta_1} - \alpha^{-\beta_1})\beta_1(\beta_1^2 \ln\alpha - \nu_{\theta r}\ln\alpha - \beta_1^2 + 1)]$$
$$+ (D_\theta + 4D_k)[2(\alpha^{\beta_1} + \alpha^{-\beta_1}) - 4 - \beta_1 \ln\alpha(\alpha^{\beta_1} - \alpha^{\beta_1})]\}/\Delta_1 b^2;$$

$$K_{21} = \pi\alpha\beta_1 D_r[(\alpha^{\beta_1} + \alpha^{-\beta_1})(\beta_1^2 \ln\alpha - \beta_1^2 + 2 - 2\nu_{\theta r}) + 2(\beta_1^2 - 2 - 2\nu_{\theta r})$$
$$- (\alpha^{\beta_1} - \alpha^{-\beta_1})\beta_1(1 + \ln\alpha + \nu_{\theta r}\ln\alpha)]/\Delta_1 b;$$

$$K_{31} = \pi\beta_1^2 D_r[(\beta_1^2 - 1)(\alpha^{\beta_1} - \alpha^{-\beta_1}) + 2\beta_1 \ln\alpha]/\Delta_1 b^2;$$

$$K_{41} = \pi\beta_1^2 D_r[(\alpha^{\beta_1} - \alpha^{-\beta_1}) - \beta_1(\alpha^{\beta_1} + \alpha^{-\beta_1}) + 2\beta_1(1 - \ln\alpha)]/\Delta_1 b;$$

$$K_{22} = \pi\alpha\beta_1 D_r[(\alpha^{\beta_1} - \alpha^{-\beta_1})\beta_1(1 + \ln\alpha + \nu_{\theta r}\ln\alpha) + 4(1 + \nu_{\theta r})$$
$$- (\alpha^{\beta_1} + \alpha^{-\beta_1})(2 + 2\nu_{\theta r} + \beta_1^2 \ln\alpha)]/\Delta_1;$$

$$K_{32} = \pi\beta_1^2 D_r[(\alpha^{\beta_1} - \alpha^{-\beta_1}) + \beta_1(\alpha^{\beta_1} + \alpha^{-\beta_1}) - 2\beta_1(1 + \ln\alpha)]/\Delta_1 b;$$

$$K_{42} = \pi\alpha\beta_1^2 D_r[2\beta_1 \ln\alpha - (\alpha^{\beta_1} - \alpha^{-\beta_1})]/\Delta_1;$$

$$K_{33} = \pi\beta_1\{D_r[(\alpha^{\beta_1} - \alpha^{-\beta_1})\beta_1(1 - \beta_1^2 - \beta_1^2 \ln\alpha + \nu_{\theta r}\ln\alpha) + 4\nu_{\theta r}$$
$$- (\alpha^{\beta_1} + \alpha^{-\beta_1})(2\nu_{\theta r} + \beta_1^2 \ln\alpha)]\}/\Delta_1 b^2$$
$$- (D_\theta + 4D_k)[2(\alpha^{\beta_1} + \alpha^{-\beta_1}) - 4 - \beta_1 \ln\alpha(\alpha^{\beta_1} - \alpha^{-\beta_1})]\}/b^2\alpha\Delta_1;$$

$$K_{43} = \pi\beta_1 D_r[(\alpha^{\beta_1} + \alpha^{-\beta_1})(\beta_1^2 + \beta_1^2 \ln\alpha - 2 - 2\nu_{\theta r}) - 2(\beta_1^2 - 2 - 2\nu_{\theta r})$$
$$+ (\alpha^{\beta_1} - \alpha^{-\beta_1})(\beta_1 \ln\alpha - \beta_1 + \nu_{\theta r}\beta_1 \ln\alpha)]/b\Delta_1;$$

$$K_{44} = \pi\alpha\beta_1 D_r[(\alpha^{\beta_1} + \alpha^{-\beta_1})(2 + 2\nu_{\theta r} - \beta_1^2 \ln\alpha) - 4(1 + \nu_{\theta r})$$
$$+ (\alpha^{\beta_1} - \alpha^{-\beta_1})\beta_1(1 - \ln\alpha - \nu_{\theta r}\ln\alpha)]/\Delta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

For $n > 1$:

$$K_{11} = \pi\alpha\{(\beta_n - \gamma_n)^2\alpha^{\beta_n+\gamma_n}[D_r(\beta_n + \gamma_n)(1 - \beta_n)(1 - \gamma_n) + n^2(\nu_{\theta r}D_r + D_\theta$$
$$+ 4D_k)] - (\beta_n + \gamma_n)\alpha^{\beta_n-\gamma_n}[D_r(\beta_n - \gamma_n)(1 - \beta_n)(1 + \gamma_n)$$
$$+ n^2(\nu_{\theta r}D_r + D_\theta + 4D_k] + (\beta_n + \gamma_n)\alpha^{\gamma_n-\beta_n}[D_r(\beta_n - \gamma_n)(1 + \beta_n)(1 - \gamma_n)$$
$$- n^2(\nu_{\theta r}D_r + D_\theta + 4D_k)] - (\beta_n - \gamma_n)\alpha^{-\beta_n-\gamma_n}[D_r(\beta_n + \gamma_n)(1 + \beta_n)(1 + \gamma_n)$$
$$- n^2(\nu_{\theta r}D_r + D_\theta + 4D_k)] + 8n^2\beta_n\gamma_n(\nu_{\theta r}D_r + D_\theta + 4D_k)\}/\Delta_n b^2;$$

$$K_{21} = \pi D_r\alpha\{(\beta_n - \gamma_n)^2\alpha^{\beta_n+\gamma_n}[(1 - \beta_n)(1 - \gamma_n) + n^2\nu_{\theta r}]$$
$$- (\beta_n + \gamma_n)^2\alpha^{\gamma_n-\beta_n}[(1 + \beta_n)(1 - \gamma_n) + n^2\nu_{\theta r}]$$
$$+ (\beta_n - \gamma_n)^2\alpha^{-\beta_n-\gamma_n}[(1 + \beta_n)(1 + \gamma_n) + n^2\nu_{\theta r}]$$
$$- (\beta_n + \gamma_n)^2\alpha^{\beta_n-\gamma_n}[(1 - \beta_n)(1 + \gamma_n) + n^2\nu_{\theta r}] - 4\beta_n\gamma_n(\beta_n^2 + \gamma_n^2$$
$$+ 2n^2\nu_{\theta r} - 2)\}/\Delta_n b; \quad K_{31} = 2\pi D_r(\beta_n^2 - \gamma_n^2)[\beta_n(1 - \gamma_n^2)(\alpha^{-\gamma_n} - \alpha^{\gamma_n})$$
$$+ \gamma_n(1 - \beta_n^2)(\alpha^{\beta_n} - \alpha^{-\beta_n})]/\Delta_n b^2; \quad K_{41} = 2\pi D_r\alpha(\beta_n^2 - \gamma_n^2)[\beta_n(1 - \gamma_n)\alpha^{\gamma_n}$$
$$- \beta_n(1 + \gamma_n)\alpha^{-\gamma_n} + \gamma_n(1 + \beta_n)\alpha^{-\beta_n} - \gamma_n(1 - \beta_n)\alpha^{\beta_n}]/\Delta_n b;$$

$$K_{22} = \pi D_r\alpha\{(\beta_n + \gamma_n)^2[(\beta_n - \gamma_n + 1 + \nu_{\theta r})\alpha^{\gamma_n-\beta_n} - (\beta_n - \gamma_n - 1$$

$$- \nu_{\theta r})\,\alpha^{\beta_n-\gamma_n}] + (\beta_n - \gamma_n)^2\,[(\beta_n + \gamma_n - 1 - \nu_{\theta r})\,\alpha^{\beta_n+\gamma_n}$$

$$- (\beta_n + \gamma_n + 1 + \nu_{\theta r})\,\alpha^{-\beta_n-\gamma_n}] - 8\,\beta_n\gamma_n(1 + \nu_{\theta r})\}/\Delta_n;$$

$$K_{32} = 2\pi D_r(\beta_n^2 - \gamma_n^2)[\beta_n(1 + \gamma_n)\,\alpha^{\gamma_n} - \beta_n(1 - \gamma_n)\,\alpha^{-\gamma_n}$$

$$- \gamma_n(1 + \beta_n)\,\alpha^{\beta_n} + \gamma_n(1 - \beta_n)\,\alpha^{-\beta_n}]/\Delta_n b;$$

$$K_{42} = 2\pi D_r\alpha(\beta_n^2 - \gamma_n^2)[\gamma_n(\alpha^{\beta_n} - \alpha^{-\beta_n}) - \beta_n(\alpha^{\gamma_n} - \alpha^{-\gamma_n})]/\Delta_n;$$

$$K_{33} = \pi\{(\beta_n + \gamma_n)^2\,\alpha^{\gamma_n-\beta_n}\,[D_r(\beta_n - \gamma_n)(1 - \beta_n)(1 + \gamma_n)$$

$$+ n^2(\nu_{\theta r}D_r + D_\theta + 4D_k)] - (\beta_n - \gamma_n)^2\,\alpha^{-\beta_n-\gamma_n}\,[D_r(\beta_n + \gamma_n)(1 - \beta_n)(1 - \gamma_n)$$

$$+ n^2(\nu_{\theta r}D_r + D_\theta + 4D_k)] + (\beta_n - \gamma_n)^2\,\alpha^{\beta_n+\gamma_n}\,[D_r(\beta_n + \gamma_n)(1 + \beta_n)(1 + \gamma_n)$$

$$- n^2(\nu_{\theta r}D_r + D_\theta + 4D_k)] - (\beta_n + \gamma_n)^2\,\alpha^{\beta_n-\gamma_n}\,[D_r(\beta_n - \gamma_n)(1 + \beta_n)(1 - \gamma_n)$$

$$- n^2(\nu_{\theta r}D_r + D_\theta + 4D_k)] - 8n^2\beta_n\gamma_n(\nu_{\theta r}D_r + D_\theta + 4D_k)\}/\Delta_n b^2\alpha;$$

$$K_{43} = \pi D_r\{(\beta_n + \gamma_n)^2\,\alpha^{\beta_n-\gamma_n}\,[(1 + \beta_n)(1 - \gamma_n) + n^2\nu_{\theta r}]$$

$$- (\beta_n - \gamma_n)^2\,\alpha^{\beta_n+\gamma_n}\,[(1 + \beta_n)(1 + \gamma_n) + n^2\nu_{\theta r}]$$

$$+ (\beta_n + \gamma_n)^2\,[(1 - \beta_n)(1 + \gamma_n) + n^2\nu_{\theta r}]$$

$$- (\beta_n - \gamma_n)^2\,\alpha^{-\beta_n-\gamma_n}\,[(1 - \beta_n)(1 - \gamma_n) + n^2\nu_{\theta r}]$$

$$+ 4\beta_n\gamma_n(\beta_n^2 + \gamma_n^2 - 2n^2\nu_{\theta r} - 2)\}/\Delta_n b;$$

$$K_{44} = \pi D_r\alpha\{(\beta_n + \gamma_n)^2\,[(\beta_n - \gamma_n - 1 - \nu_{\theta r})\,\alpha^{\gamma_n-\beta_n}$$

$$- (\beta_n - \gamma_n + 1 + \nu_{\theta r})\,\alpha^{\beta_n-\gamma_n}] + (\beta_n - \gamma_n)^2\,[(\beta_n + \gamma_n + 1 + \nu_{\theta r})\,\alpha^{\beta_n-\gamma_n}$$

$$- (\beta_n + \gamma_n - 1 - \nu_{\theta r})\,\alpha^{-\beta_n-\gamma_n}] + 8\beta_n\gamma_n(1 + \nu_{\theta r})\}/\Delta_n \quad \ldots\ldots\ldots\ldots \quad (33)$$

Stiffness Coefficients: Circular Element.—There are three 2 × 2 element stiffness matrices for a typical polar orthotropic circular element corresponding to the 0th, 1st, and nth harmonics. The sign convention for all forces and stiffness coefficients are consistent with the nodal circle displacements shown in Fig. 2.

For $n = 0$:

$$K_{11} = 0, \quad K_{12} = K_{21} = 0; \quad K_{22} = 2\pi D_r(k + \nu_{\theta r}) \quad \ldots\ldots\ldots\ldots\ldots \quad (34)$$

For $n = 1$:

$$K_{11} = \pi\,[\beta_1(\beta_1 + 1)\,D_r - (D_{r\theta} + D_\theta + 2D_k)]/a^2;$$

$$K_{12} = K_{21} = -\pi D_r(1 + \nu_{\theta r} + \beta_1)/a; \quad K_{22} = \pi D_r(1 + \nu_{\theta r} + \beta_1) \quad \ldots\ldots \quad (35)$$

For $n > 1$:

$$K_{11} = \pi\{D_r\,[(1 + \beta_n)(1 + \gamma_n)(\beta_n + \gamma_n)] - n^2(D_{r\theta} + D_\theta + 2D_k)\}/a^2;$$

$$K_{21} = K_{12} = -\pi D_r\,[(1 + \beta_n)(1 + \gamma_n) + n^2\nu_{\theta r}]/a;$$

$$K_{22} = \pi D_r(1 + \beta_n + \gamma_n + \nu_{\theta r}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (36)$$

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Appendix IV.—Notation

The following symbols are used in this paper:

a = outer radius of annular ring;
b = inner radius of annular ring;
$D_k = G_{r\theta}t^3/12$ = shearing rigidity;
$D_{r\theta} = \nu_{\theta r}D_r + 2D_k$ = twisting rigidity;
$D_r = E_r t^3/12(1 - \nu_{\theta r}\nu_{r\theta})$ = radial plate rigidity;
$D_\theta = E_\theta t^3/12(1 - \nu_{\theta r}\nu_{r\theta})$ = hoop plate rigidity;
E_r = radial elastic modulus;
E_θ = hoop elastic modulus;
$F_n(r)$ = nth radial component of displacement function;
$G_n(\theta)$ = nth circumferential component of displacement function;
$G_{r\theta}$ = shear modulus;
$j^2 = 2D_k/D_r$;
$\mathbf{K}$ = overall stiffness matrix;
$\mathbf{K}_n$ = nth harmonic stiffness matrix;
$k^2 = D_\theta/D_r$;
n = harmonic;
P = concentrated force;
$P^*(r,\theta)$ = Fourier series representation of concentrated force;
$q(r,\theta)$ = distributed load;
r = radial coordinate;

t = plate thickness;
U = strain energy;
$\mathbf{W}$ = displacement vector;
$w(r, \theta)$ = plate deflection at radial coordinate r, circumferential coordinate θ;
w_1 = $(w_1 = \Sigma w_{1n})$ translation at nodal circle $r = b$, $\theta = 0$;
w_2 = rotation at nodal circle $r = b$, $\theta = 0$; $(w_2 = \Sigma w_{2n})$;
w_3 = translation at nodal circle $r = a$, $\theta = 0$; $(w_3 = \Sigma w_{3n})$;
w_4 = rotation at nodal circle $r = a$, $\theta = 0$; $(w_4 = \Sigma w_{4n})$;
w_{1n} = nth translation component at nodal circle $r = b$, $\theta = 0$;
w_{2n} = nth rotation component at nodal circle $r = b$, $\theta = 0$;
w_{3n} = nth translation component at nodal circle $r = a$, $\theta = 0$;
w_{4n} = nth rotation component at nodal circle $r = a$, $\theta = 0$;
α = a/b;
γ_{ij} = coefficients comprising shape functions;
$\Delta_0, \Delta_1, \Delta_n$ = nondimensional ratios (see Appendix I);
θ = circumferential coordinate;
$\nu_{\theta r}, \nu_{r\theta}$ = Poisson ratio;
$\rho_j(r)$ = jth function of r; and
$\phi_{in}(r)$ = ith shape of interpolation function for harmonic n.

REMOTE SENSING FOR NUCLEAR POWER PLANT SITING[a]

By Barry S. Siegal[1] and Charles W. Welby[2]

(Reviewed by the Aerospace Division)

INTRODUCTION

The siting of nuclear power plants requires a multidisciplinary and phased program which addresses many technical, licensing, and socioeconomical factors. To insure responsible design and engineering, the siting and evaluation process requires input from various disciplines to address properly issues of safety, environmental impact, site development requirements, and proximity to load demand.

Although geologists and seismologists must provide critical design information, one of the most crucial aspects of their involvement is to stipulate the design basis for maximum vibratory ground motion. The earthquake which could cause maximum vibratory ground motion at the site [designated the Safe Shutdown Earthquake (SSE)], is established by determining the effect of the most severe earthquakes associated with a capable fault or within a seismo-tectonic province. Capable faults are defined as having moved at least once within the past 35,000 yr, recurrently within the past 500,000 yr, or having a record of macroseismicity. Seismo-tectonic provinces are regions characterized by like geologic structural features and seismicity. (In establishing the SSE it is assumed that any historical earthquake associated with a capable fault could have occurred with the epicenter where the fault is nearest the site. The length of the fault is also important in determining possible rupture length and maximum earthquake. Earthquakes that cannot be associated with capable faults are assumed to be "random earthquakes" and therefore likely to occur anywhere within their seismo-tectonic province. For design purposes, the epicenter of the maximum-magnitude random earthquake is assumed to occur at its closest approach to the site within its seismo-tectonic province.) Estimates of the SSE are crucial in the early stages of site selection and evaluation and can be derived from consideration of the

[a]Presented at the October 22–26, 1979, Annual Convention and Exposition, held at Atlanta, Ga.

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on August 12, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0317/$01.00.

seismic history and structural and tectonic analysis of the region.

Remote sensing techniques provide a cost effective and time efficient approach in establishing seismo-tectonic provinces and in delineating the possible extent of seismogenic structures. These techniques also provide definitive information on various engineering-related characteristics of the terrain (such as landslide potential and type of material), potential hazards, and in the planning of field programs.

This paper considers some of the many uses of remote sensing in selecting and evaluating potential nuclear power plant sites. Specific examples are cited from studies conducted in evaluating sites in the Philippines and Mexico.

Considerations

The remote sensing techniques used in siting studies depend upon many geologic and economic factors. Unfortunately, in some instances economics dictate what imagery can be acquired and what processing undertaken. In siting investigations for developing nations, where geologic information is scarce or of poor quality, acquisition of radar imagery provides much needed information on regional structures and geomorphology. Side-Looking Airborne Radar (SLAR) is particularly important in regions with extensive cloud cover and inclement weather.

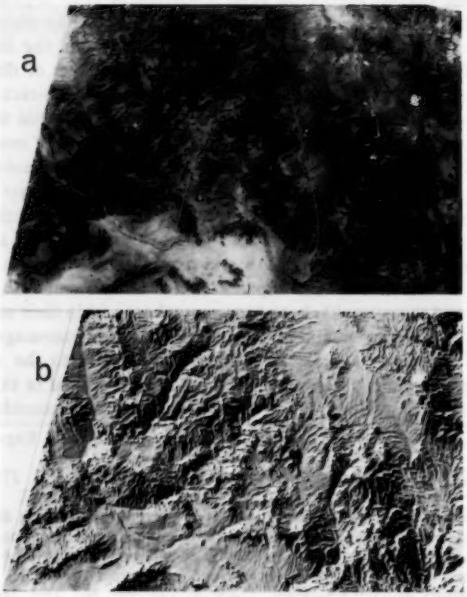

FIG. 1.—Comparison of Landsat MSS Image: (*a*) and Low Angle SW Illuminated Plastic Relief Map; (*b*) for an Area Near Prescott, Ariz. (2)

Wherever possible, SLAR should be obtained for as much as 10,000 km^2 around the potential site to insure adequate coverage of regional tectonic features. Satellite imagery, particularly Landsat MSS data, should be obtained at appropriate scales. When available, the data should be acquired in digital form [on computer compatible tapes (CCT's)] to permit use of image enhancement techniques. Color additive viewing and allied photographic enhancement techniques can prove valuable when dealing with multispectral imagery. Aerial photography (particularly color and color IR) should be acquired for the site area, at scales of 1:24,000 or better, for mapping of such features as fracture

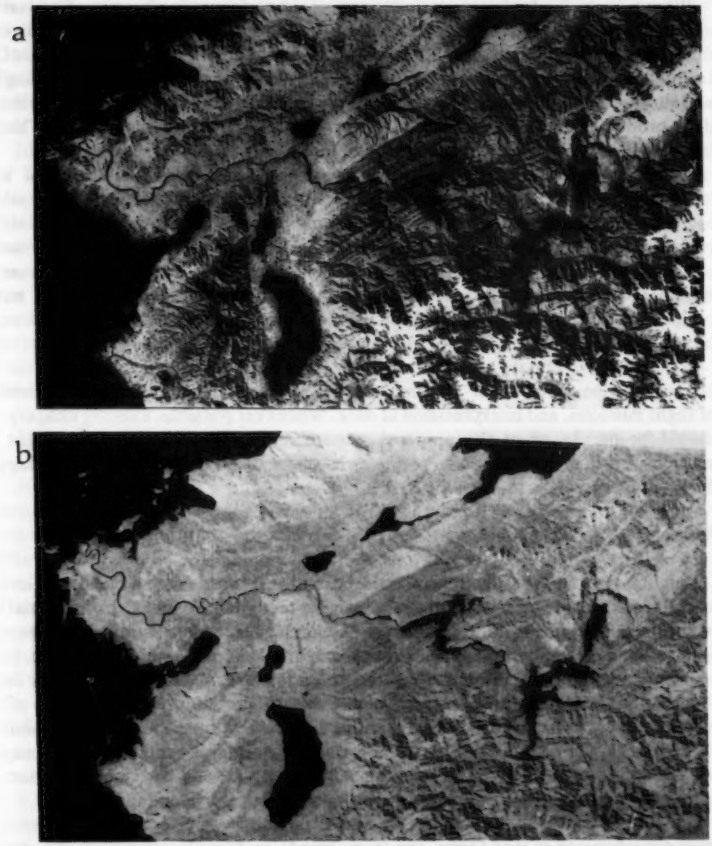

FIG. 2.—Significance of Low Sun Angle and Snow Cover for Mapping Topographically Controlled Linear Features: (*a*) Landsat Scene Acquired January 31, 1973 (Sun El. 27°); (*b*) Landsat Scene Aquired September 8, 1972 (Sun El. 49°)

traces and landslide scarps. If possible, thermal IR imagery should be obtained to help delineate fracture traces. The advantages of predawn thermal IR imagery for fracture trace mapping has been described by various workers (1).

Plastic relief maps can also be used in the early stages of siting studies to delineate topographically controlled linear features that may represent the surface expression of structure. These maps are illuminated at low angles from varying directions and photographed, providing various look directions that can be studied in conjunction with Landsat and SLAR images (Fig. 1). (Notice distinct enhancement of topographically controlled linear feature.) The significance of these photographs have been described by Wise (5).

Where coastal circulation patterns are of importance to the site, Landsat and the National Oceanic and Atmospheric Administration (NOAA) imagery may be studied individually and collectively using photographic enhancement techniques. Suspended sediment and thermal patterns provide clues to upwelling and surface circulation even on individual images. Repetitive satellite photographic data products allow interpretation for various meteorological conditions. This information can be obtained relatively inexpensively.

Proper selection of imagery is critically important in the initial stages of a siting investigation. Whenever possible, low sun-angle images should be obtained to show maximum topographic relief. Snow cover can also be beneficial, particularly in regions of relatively low relief. Fig. 2 shows the better definition of topographically expressed features on Landsat impages acquired at low sun angles and snow cover for the Pindus Mountains area in western Greece, an outlining area presently under study in an overall siting study for the first nuclear power plant in Greece.

Scheduling of remote sensing activities must receive high priority because of the lag time involved in securing existing imagery, planning and execution of flight missions, and interpretation of data. Whenever possible, existing imagery should be purchased at the proposal stage and details worked out for flight missions, so that contracts can be prepared and executed shortly after signing the study contract.

Approach

Remote sensing investigations should be initiated with seismological studies to delineate seismogenic structures and seismo-tectonic provinces. In the initial remote sensing investigation, emphasis should be placed on identifying linear features and determining the maximum extent of known faults to insure a conservative approach in estimating the potential SSE. Particular attention is focused on linear features near coastal areas to permit proper planning of overwater geophysical surveys. All identified linear features, known faults, and epicenters should be compiled on maps for analysis. In assessing such analyses, consideration must be given to operator subjectivity (2) and a weighting factor approach should be used when more than one investigator is involved.

Geomorphologic studies can be used to establish seismo-tectonic provinces from consideration of land forms, structural trends, and epicentral data. A change in structural trend frequently occurs between seismo-tectonic structures, particularly those related to plate tectonic boundaries. Geomorphologic studies are also used to estimate the relative ages of different units; this is particularly

important in mapping, and in volcanic terrains. Such studies can be used to guide field sampling programs and to identify potential hazards resulting from mass movements (landslides, mudflows, etc.) or liquifaction. In volcanic terrains where age dating of extrusive materials is important, clues to relative ages of flows, lahars, and ash deposits may be worked out prior to the initiation of a sampling program.

Digital processing and photographic enhancement techniques can improve image display and interpretability. The particular techniques used depend upon the imagery available, interpreter capability, and scheduling considerations. When data are amenable to digital processing, image enhancement techniques should be employed to maximize data extraction. High pass spatial filtering enhances the high frequency component of the image, facilitating structural interpretation. Contrast stretching permits utilization of the dynamic range of the display medium. Photographic techniques including false-color compositing of various data products, often brings out variations in spectral reflectance and texture which are not evident in black and white images.

Ideally, remote sensing studies should be conducted sufficiently far in advance of field activites to obtain and develop all image products and interpretative maps. Since these studies are rarely completed before field reconnaissance begins, the interpreter must make value judgements on which areas and features require consideration or should be deleted from further study because of the large uncertainties and economic risk. This underlying philosophy is also used at the initial stage of siting by other members of the project team to evaluate potential regions, taking into account the known conditions and assigning low ratings to areas which have unknown, poorly known, or unacceptable conditions.

Applications

This section outlines some of the remote sensing studies conducted in evaluating potential nuclear power plant sites in the Philippines and Mexico.

Nuclear Power Plant Siting, Republic of The Philippines.—A comprehensive remote sensing study was conducted as part of an overall site selection/evaluation study for siting the first nuclear power plant in the Republic of the Philippines. The site selection study, initiated in 1973, was part of a continuing 10-yr study conducted by the International Atomic Energy Agency, Philippine Atomic Energy Commission, and the Philippine National Power Corporation (NPC). The remote sensing investigation was designed to provide baseline data for evaluating three microregions within the Bataan Peninsula, which were selected on the basis of the previous studies. North to south, these regions are: (1) The southern tip of Zambales Peninsula; (2) the area within 10 km of the Barrio of Bagac; and (3) the southern tip of Battan Peninsula, typified by San Jose Point. The specific objectives of the remote sensing study included the following:

1. Identifying linear features that could be the surface expressions of faults or fractures.
2. Locating volcanic centers.
3. Determining stratigraphy and relative geochronology between the volcanic and tectonic events within the Zambales-Bataan volcanic highlands.
4. Locating coastal and near-shore hot springs and delineating zones of

suspended offshore sediment concentration and movement.

Information from the remote sensing study and other studies was used to select potential sites and to prepare the required Safety Analysis Reports.

The first phase of the study was the planning and execution of a flight mission to obtain SLAR and aerial photography. The SLAR imagery, using the Motorola APS/AN94-D (X-band) real-aperture system, was obtained for 10,000 km^2,

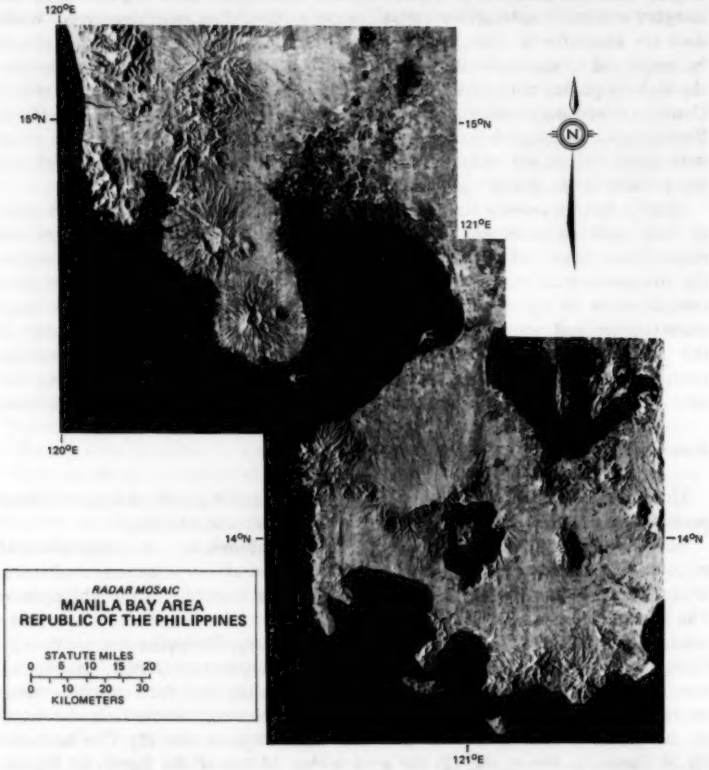

FIG. 3(*a*).—Manila Bay Area of Republic of Philippines: Eastlook SLAR Mosaic

extending from Mt. Pinatubo, south to the Taal-Banahao volcanic area, and from the west coast of Luzon, east to Laguna de Bay (Figs. 3 and 4). Flight lines were north-south with a two-look direction. Contact prints were prepared from the 1:250,000 acquisition scale, enlarged to 1:100,000 scale for more detailed study.

Color and black and white aerial photographs at a scale of 1:8,000 were obtained for the Bataan Peninsula coastline, from Eman Point south to Caybobo

Point. Black and white aerial photographs at scales of 1:8,000 and 1:15,000 were obtained within a 10-km radius of Bagac and were used to supplement

FIG. 3(*b*).—Manila Bay Area of Republic of Philippines: Reference Map

existing 1:15,000-scale black and white aerial photographs of the entire Bataan Peninsula and the 1:20,000 photographs for the Mapalan Point region.

A predawn flight, using a Daedalus 60-thermal infrared line-scanner, a 0.5-milliradian spot size, and a 0.1° C temperature-sensitivity, acquired thermal

infrared imagery for the entire coastline of the Bataan Peninsula. Because of the dense vegetation cover and extreme topographic relief, no flight was planned over the volcanic highland area.

The initial phase of the remote sensing study included the delineation of linear features that could be significant to a potential site if they represented capable faults. In evaluating the three microregions, SLAR images revealed distinct pervasive fracturing within the Zambales region (Fig. 4). Available information also suggested that major faults are common, the closest forming the boundaries of the east-west-trending San Antonio Graben. Although the areal extent of these faults had been generally mapped, analysis of the SLAR images suggested their extent might be greater than previously indicated, conceivably resulting in a relatively high SSE value for a site in this region. Extensive field investigations would be required to determine capability of these linear features.

FIG. 4.—Enlargment of SLAR Image for Bataan Peninsula

The southern Bataan microregion can be seen on SLAR images as a broad, gently sloping fan of volcanic material originating from the summit of Mt. Mariveles. Although no evidence of faulting was suggested by examination of SLAR and Landsat images, the susceptibility of a site in this region to potential damage from even small volcanic events would make licensing difficult. In addition, magnetic maps of the area showed a possible structural feature directly offshore San Jose Point, which appeared to correlate with an area of seismic activity.

The Bagac region was found to be underlain by a thick sequence of pyroclastic rocks related to the Mt. Natib and Mt. Mariveles volcanic areas. No evidence of faulting in the site region was found on imagery or during field reconnaissance. Furthermore, there are no historical epicenters in the region and imagery suggested that several parts of it would provide excellent protection from volcanic hazards. The advantages of the Bagac region over the Zambales and Southern Bataan regions suggested it should be considered the candidate site area.

Six specific sites within this region were selected for detailed analysis: (1) Napot Point; (2) Mapalan Point; (3) Bagac I and II; (4) Saysain Point; and (5) Caybobo Point. Caybobo Point was eliminated early because it lacks natural protection from volcanic activity. Mapalan Point was eliminated because it displayed morphological characteristics suggesting it was part of a large slide block that had rotated and moved 1 km–2 km downslope on Mt. Natib. Although the topography of the area would provide excellent protection from volcanic hazards, existence of a possible glide plane beneath the point ended consideration of Mapalan Point as a primary site. Saysain Point was eliminated because it lacks natural protection from volcanic events and is characterized by a deep weathering profile. Both Bagac sites were eliminated because they lacked natural protection from volcanic events and are characterized by a deep weathering profile. In addition, aerial photography showed them to be possibly subject to river and tsunami flooding. The Napot Point site appeared to afford a high degree of natural protection from volcanic events and no threat of flooding or tsunami damage. Other evidence suggested good foundation considerations, and it was chosen as the preliminary primary site.

After selection of the Napot Point site, extensive investigations permitted thorough evaluation of seismic and volcanic risks to the proposed plant and fulfilled all nuclear licensing requirements. During the site confirmation studies, image analysis was used in a variety of ways to guide field investigations and help establish the seismological and volcanological data base. A primary activity was tracing the extent of known faults within 100 km of the site to assist in estimating and refining the SSE. The trace of the San Antonio Graben, a SSE generator, is clear on both SLAR and Landsat images. On Landsat images, the distinction results primarily from a tonal change due to difference in spectral reflectance between the ultramafic rocks of the Zambales Mountains and the surficial covering of Holocene sediments within the graben. The northern boundary of the graben is conspicuous topographically and is partly outlined by the Santo Tomas River; tone and topography make the southern boundary distinct on the imagery.

Topographic change across the graben is particularly distinct on SLAR images. Variations in tonal expression of the graben and the adjacent region are due to an apparent difference in the surface roughness of the ultramafic rocks of

the Zambales Mountains and the Holocene sediments of the graben. The SLAR and Landsat images were also important in determining relative age of volcanic materials and in directing the field-sampling program. Color renditions of this imagery enhanced boundaries of individual flow units. A total of 52 samples from lava flows and instrusive bodies were collected within the site region and dated radiometrically. The temporal distribution was determined, using time-series analysis techniques developed by Stepp (3) and Wickman (4). In general, the correlation between the degree of erosion of volcanic material and its age is good, the older material is more dissected.

Stereoscopic analysis of adjacent SLAR strips (same look direction) proved invaluable during the investigation, particularly in evaluating linear features. The significance of such enhancement can be seen on the different northwest-trending linear features on the western flank of Mt. Natib (Fig. 4). The apparent distinctness of these linear features appears to result primarily from "shadow" enhancement, as reported by Wise (5), from a study of raised plastic relief maps photographed from different directions, under varying illumination. Analysis of deviations of the linear features from maximum enhancement conditions stipulated by Wise (5) revealed that their distinctness is primarily a function of illumination.

Stereoscopic analysis of side-lapping SLAR strips (primarily from east-look direction) further revealed that the features are erosional channels that do not breach the rim of Mt. Natib and extend to Olongapo Bay, as might be suggested from casual observation of the SLAR mosaic. In fact, they trend westward only until they intersect a low-lying rim near Bisay River; drainage is then southwest into Bisay River. The northwestward-trending erosional channels within the Mt. Natib crater do not lie along the same projection line as the linear features on the flank of the crater.

Site Evaluation Studies, Laguna Verde, Mexico.—A remote sensing study was recently performed for Comision Federal de Electricidad (CFE) to supplement geologic studies conducted by CFE for the Laguna Verde Nuclear Power Plant. Because of the supplementary nature of these studies, only satellite and aerial photography were obtained and examined. The CCT's of Landsat MSS data were obtained and processed using high-pass spatial filtering and linear contrast stretching. A double pass with a 21 × 21 (pixel) box filter was performed to enhance subtle differences, minimize "ringing" effects, and preferential enhancement of the scene. Skylab-4 color, color infrared, and black and white photographs at a scale of approximately 1:300,000, were also examined and interpreted in conjunction with conventional low altitude black and white aerial photography. Emphasis was directed at confirming findings of CFE geologists on regional structures, and in identifying all linear features within the site area to insure field study and verification.

Figs. 5 and 6 present Landsat MSS band 7 linear contrasted stretched and high pass spatially filtered images of the Laguna Verde region. The linear contrast stretched image presents a good display of the entire scene, but because of pronounced spectral reflectance difference between the water and adjacent coastal areas in the southeastern portion of the scene and the highland areas in the northwestern portion, subtle difference within these areas are not optimally displayed, making structural interpretation difficult. This particular problem is frequently encountered when the scene contains materials which have pronounced

spectral reflectance differences, such as clouds and water; play areas and basalt flows. The problem may be overcome by restricting the area of interest within the scene or through the "artificial" reassignment of gray values to different portions of the probability density function (PDF). Unfortunately, the latter

FIG. 5.—Linear Contrasted Landsat MSS Band 7 Image for Laguna Verde Nuclear Power Plant Area

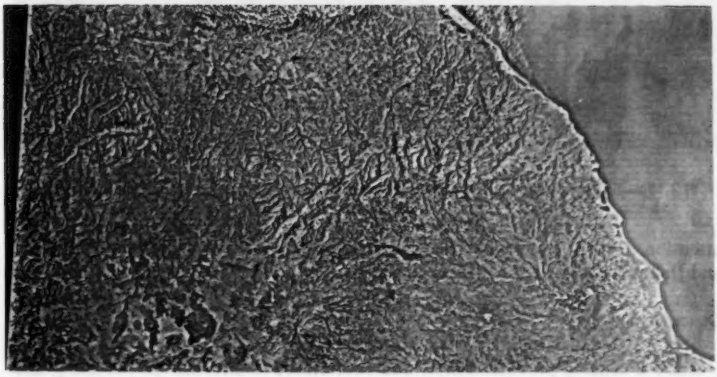

FIG. 6.—High Pass Spatially Filtered Landsat Image of Laguna Verde Nuclear Power Plant Area (Compare with Fig. 5)

approach, makes correlation between photographic graytone and ground reflectance impossible.

High pass spatial filtering using unweighted box filtering techniques provides effective edge enhancement that can be used to identify faults and joint sets. Fig. 7 shows a closeup of the near coastal area north of Laguna Verde. A

distinct northwest trending joint set can be seen approx 30 km from the coastal area. The scene also displays sediment patterns offshore. Additional computer processing of this scene would probably not improve the display significantly because of the relatively poor quality of the original image and the high sun angle. Unfortunately, cloud free better quality images were not available at the time of this investigation. Nevertheless, the use of digital processing techniques in conjunction with standard photography interpretation of aerial photographs and Skylab-4 photographs revealed several features that were called to the

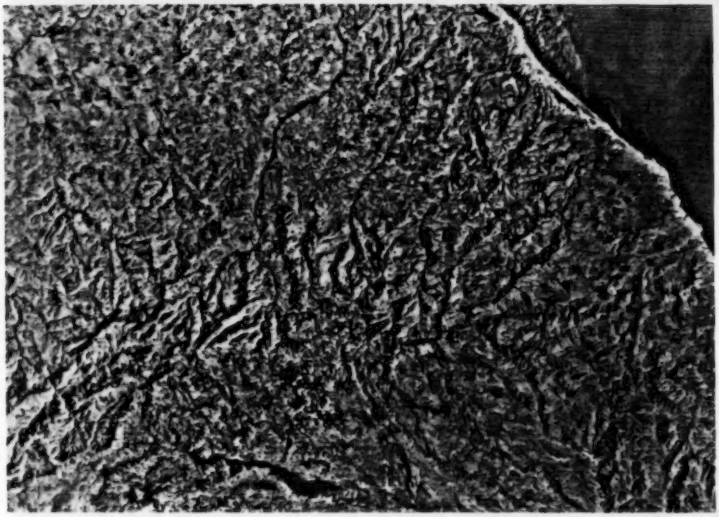

FIG. 7.—Enlargement of High Pass Spatially Filtered Image Near Coastal Area

attention of CFE geologists. The overview provided permitted efficient planning and field checking.

Conclusions

Remote sensing provides timely and cost effective information for siting and site evaluation of nuclear power plants. Efforts spent in planning remote sensing investigations will pay off in providing appropriate imagery at correct scales. Whenever possible, a flight mission should be planned and executed to insure acquisition of the best and fullest imagery for the particular terrain and conditions. SLAR imagery is particularly valuable in regions of prolonged cloud cover and haze and provides additional insurance in siting and licensing. A wide range of enhancement techniques should be employed and where possible different types of images should be color-combined to provide structural and lithologic information. Coastal water circulation over wide areas can also be studied through

repetitive coverage and synoptic nature of imaging satellites. Plastic relief maps can also be used, particularly in the early stages of site evaluation, to call attention to major topographically expressed linear features.

Remote sensing studies should be undertaken in conjunction with seismology studies, particularly in the early stages of investigation to identify specific features for field checking. When properly conducted, remote sensing investigations provide a basis for planning and execution of field activities required in siting investigations.

Acknowledgment

The writers are grateful to the NPC, Republic of The Philippines, for providing the opportunity to undertake the study cited in this paper and permission to share the results with the scientific community. Appreciation is also extended to CFE and Fred Mooser, CFE geologist, for conversations on Mexican geology and the Laguna Verde Nuclear Power Plant.

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NUCLEATED URBAN GROWTH EFFECTS ON TRANSPORTATION ENERGY CONSUMPTION

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(Reviewed by the Urban Transportation Division)

INTRODUCTION

Concern for conserving fuel in urban passenger transportation has been focused at the national level, and largely on modifications to vehicle technology. These efforts include establishment of corporate average fuel economy standards, the search for new fuel sources, and studies of new kinds of engines. This is a national problem, not only because of the scope of the issue and its influence on the economy and balance of payments, but also because local government can have little, if any influence on transportation technology.

Local government can, of course, have some control over the performance of urban transportation systems. Efforts to reduce automobile congestion and to increase the utilization of public transportation are common in cities, although their impact on energy consumption, at least in the short term, is less than apparent, since many system service and usage changes are in progress at any given time.

There may also be locally-focused opportunities to control transportation energy consumption by influencing the demand side of the travel equation, i.e., by discouraging the demand for travel, or encouraging that demand to be manifested in more economical ways. The use of parking pricing, flextime, and staggered work hours reflect efforts to influence travel demand.

Yet, if we recognize the fundamental maxim that the demand for transportation derives directly from the spatial arrangement and density of activities—land use—it appears that local governments may have at hand some additional opportunities for influencing transportation energy consumption through directing

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on July 25, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0331/$01.00.

travel demand. While it is clear that land use patterns change only slowly, decisions which influence the future land use patterns in a community are made on a daily basis. For example, governments make choices about zoning modifications (what uses and densities are permitted on a land parcel), driveway permits (what uses may have direct street access and where), building permits, taxation of land and buildings, and the provision of urban services and infrastructure (transportation, water supply, waste water treatment, schools, etc.); all of these have some influence on future land use patterns.

Thus, while the consequences of such choices may be measured in the long run, the opportunities to make the choices themselves are very much in the present. The research described in the following is based on the premise that if certain generalized land use patterns are more energy efficient than others, at least from the perspective of the energy used in passenger transportation, then it behooves local decision makers—and the planners who support them—to be aware of the relationships between day-to-day decisions affecting land use and the resultant energy consumption levels. Such an awareness may contribute, over a longer period of time, to savings in transportation energy no matter what the characteristics of the transportation technology may be.

Overall Approach

The approach adopted for this research was to construct and employ relatively simple digital simulation models to investigate the relationships between energy consumption in passenger transportation and urban form and related policies. While an empirically-based analysis might be more desirable if the results are to guide action decision making, gathering the necessary data on urban structure and energy consumptions would have been costly and difficult. Some parallel studies have used optimization models, but the products of such efforts have been somewhat idealistic and have implicitly assumed a higher degree of land use control than may in fact exist (5). The simulation approach offers the advantage of quick, inexpensive results which could be used to justify further investments in empirical analysis, while perhaps providing more realism than available from optimization strategies.

While many tools are available which would permit the simulation of travel requirements based on assumed or given urban structures [e.g., the Federally sponsored Urban Transportation Planning System (UTPS) system], an important element of the approach used here was to develop a modeling system which reflected the mutual interaction between transportation and land use (3). Rather than beginning with a land use pattern and then deriving the travel requirements in a single step, it was recognized that assumptions and policies regarding the transportation system (and the way residents use that system) influence the land use pattern. As a consequence, a set of interlinked models was assembled to replicate the equilibrium process through which transportation and land use influence each other.

The generalized model structure is shown in Fig. 1, and reported in detail elsewhere (3). It comprises the following major models: (1) A Lowry-type land use model; (2) a binomial logit modal choice model; (3) a capacity-restrained equilibrium highway assignment model; and (4) a model to sum energy consumption on each link of the transportation network.

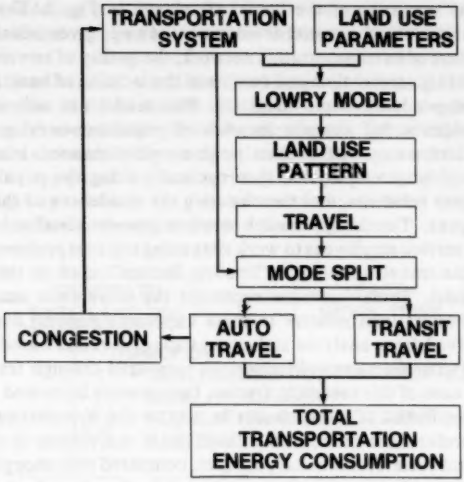

FIG. 1.—Transportation/Land Use Relationship as Reflected in Simulation Model

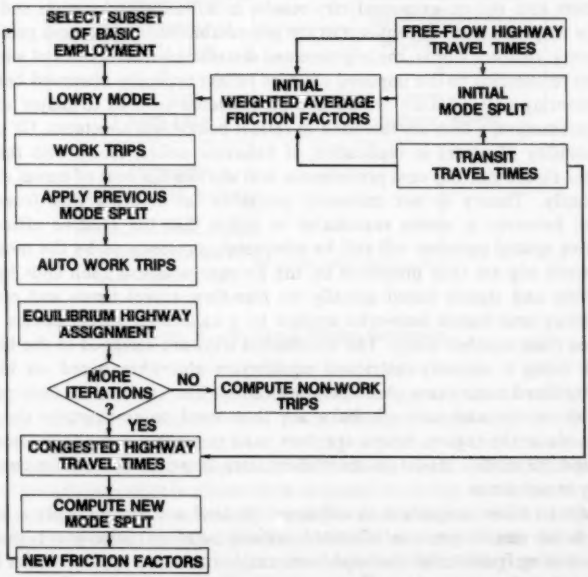

FIG. 2.—Transportation/Land Use Equilibrium Process within Simulation Model

Details of the operation of the model are shown in Fig. 2. The Lowry-type land use model simulates the spatial development of a city given initial assumptions about the structure of its transportation network, the quality of service on elements of that network (e.g., travel time and cost), and the location of basic ("exporting" or nonlocally dependent) employment (2). This model not only simulates the location of residents, but also the location of population-serving employment such as retail businesses. It functions in an iterative manner, initially locating the residences of basic employees, then cyclically siting the population-serving jobs serving these residents, and then locating the residences of the population-serving employees. The Lowry model location process distributes workers to home sites and service employees to work sites using trip cost preference functions analogous to the travel time-based "friction factors" used in the gravity trip distribution model. These functions represent the preference among travelers for cheaper (shorter) trips relative to more expensive (longer) trips. They are empirically derived from analyses and curve fitting exercises based on observed trip length and cost frequency distributions measured through travel behavior surveys; in the case of this research, friction factors were borrowed and adjusted from studies conducted in cities similar in size to the hypothetical study city. The trip cost preferences reflect the willingness of individuals to accept longer trips for work and social recreational purposes, compared with shopping purposes, because the former choice processes are more selective than the latter (6).

The simulation of location and travel processes within the model system is strongly influenced by these trip cost preference functions. The introduction of clusters into the experimental city results in subsequent location and travel behavior responses which conform to the pre-established (input) cost preference parameters. In other words, the trip time and distance characteristics of simulated travelers responding to the imposed clusters reflect typically observed behavior. The clustering pattern itself would not be expected to lead to major changes in the parameters, which are intended to reflect behavioral constants. Of course, the possibility of errors in replication of behavior exists, along with the more important threat that trip cost preferences will shift as the cost of travel changes significantly. Theory is not currently available for treating this forecasting problem; however it seems reasonable to argue that the relative efficacy of alternative spatial patterns will still be adequately represented by the model.

The work trip set thus predicted by the Lowry Model, is then split between automobile and transit based initially on free-flow travel times and costs on the highway and transit networks applied to a calibrated modal choice model borrowed from another study. The automobile trips are assigned to the highway network using a capacity-restrained equilibrium algorithm based on highway link generalized costs (time plus operating costs). The equilibrium flow patterns across all modes and network links are then used to re-estimate the travel impedances in the region, which are then used to pursue subsequent iterations of the land use model. Modal choice in these later iterations is based on congested highway travel times.

In order to allow congestion to influence the land use pattern, only a fraction of the basic employment is allocated initially, and in subsequent iterations ever-increasing fractions of the total basic employment are applied to the Lowry model so that the congestion effects, specifically considered in the assignment model, become increasingly severe (and realistic) as the model converges on

an equilibrium solution (see Fig. 2). The result is an estimate of both the overall land use pattern and transportation system utilization which are in balance with each other.

Based on the pattern of population and employment produced by the land use model, a series of travel models is used to simulate the shopping, nonhome-based, and social recreational travel in the region. These trips are also split by mode and the automobile trips assigned to the highway network. Total gasoline consumption is computed by summarizing across all trip purposes, for each link in the highway network, the fuel consumed by vehicles (autos and buses) traveling on that link at the speed used in the assignment.

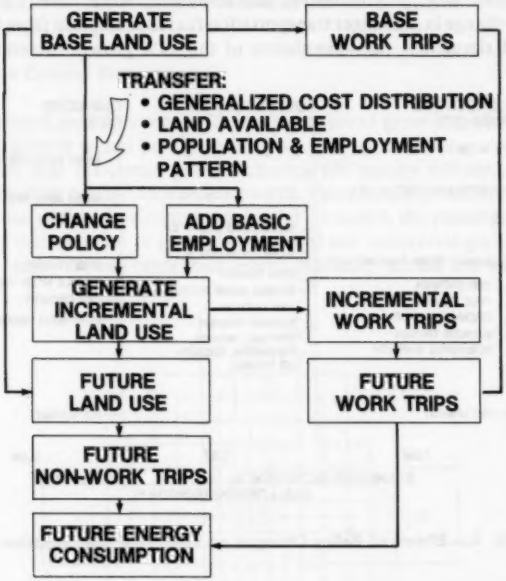

FIG. 3.—Dynamic Model Structure

One more nuance was included in the modeling system to recognize that the likely land use consequences of policy changes would only occur through the growth process in the city; i.e., during a period of one decade to three decades, the existing land use pattern and building stock will not change much, but new growth may shift in character in response to energy conservation policies. This is accomodated by permitting a policy—land use control or transportation investment—to be defined and introduced into a base city. Then, the simulation model is permitted to cycle through the consequences of a 25% growth increment, to isolate the energy consumption impacts of the policies to be tested (see Fig. 3).

The result is a model which permits the testing of various conservation policies by simulating the passenger transportation energy consumption for a given, hypothetical city, both in a base condition and with the implementation of specific policy changes. This permits the assessment of the policies themselves in terms of the resultant land use, travel, and transportation energy consumption outcomes—given a 25% population growth increment during the evaluation period.

Findings of Earlier Work

Results of an earlier phase of this research, using a city with an initial population of 100,000, are summarized in Fig. 4. In this part of the work, three city shapes, i.e., concentric ring, polynucleated, and one-sided, were tested. Fig. 4 shows percentage change in passenger transportation fuel consumption from the standard incremental simulation run—simulation of the 25% growth increment with no

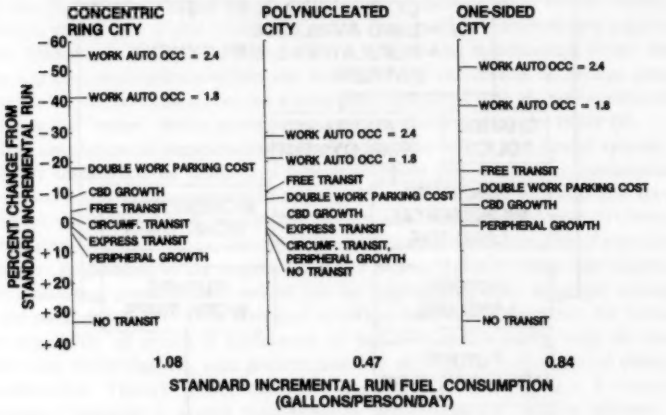

FIG. 4.—Effects of Policy Changes on Total Fuel Consumption

policy changes—for each city type. Several points are evident from this figure and other findings in that (3): (1) There are substantial differences in energy consumption under some of the policies tested; (2) the one-sided city, which is effectively one-half of the concentric ring city, responds to policies much like the concentric ring shape; the polynucleated shape *seems* more energy efficient, *and thus* shows much less response to the policies tested; (3) transit improvements have relatively little impact on energy consumption, but eliminating transit has a large negative effect, indicating the important role which transit plays in reducing peak hour congestion; and (4) centralized urban growth seems more energy efficient than growth at the periphery of the city, i.e., higher central densities lead to lower energy consumption than urban sprawl.

While the latter finding may be intuitively obvious, this outcome, and the high energy efficiency of the polynucleated city, led to the decision to explore

in more detail the transportation energy consequences of encouraging growth nuclei or clusters in various locations.

This research focused on a small city for purposes of computational economy and clarity of results. Transferring the findings to larger cities seems reasonable, but it must be recognized that the spatial structure of large urban areas tends to be quite complex. This will constrain the direct and detailed translation of numerical results, although the general findings are likely to remain valid.

In addition to requiring major increases in computational burden, application to larger cities would require adjustments to the travel behavior parameters, especially the trip cost preference functions, to reflect the existence of opportunities for longer trips. Still, the general form of these functions should not need to be modified, and the structural basis for the model system should remain applicable.

Framework for Current Research

If concentrated growth is more efficient than spread growth, perhaps a policy of nucleated growth would be a promising way to control energy consumption. To the extent that off-center growth clusters are energy efficient, they may represent a feasible option to sprawled growth. Therefore, this research explored, through the use of the aforementioned simulation model, the passenger transportation energy consumption of a variety of central and noncentral growth clusters.

Of course, many factors other than energy efficiency should and will influence

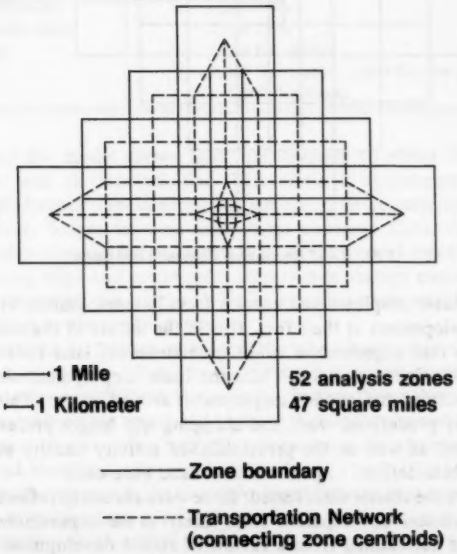

FIG. 5.—Hypothetical Concentric Ring City

land use and urban development policy choices. These will include urban finance and tax base, availability of land, equity considerations, and the social and economic factors not considered in this model which are clearly important in determining the behavior of individual locators. Still, information on relative energy efficiency of alternative land use patterns and policies may be of use, together with other locally-specific information, in guiding choices which are wise in energy and other terms.

The hypothetical city used in this research is a concentric ring structure 8.5 mile (14.2 km) on a side, having an initial population of 100,000. Its average density is 2,127 people/sq mile (821/km^2). It is shown, along with its highway network, in Fig. 5. Transit is in the form of bus routes operating at 20-min headways and focused on the central business district (CBD).

Four cluster types were tested in various locations, starting at the center of the city and moving outward to the edge (see Fig. 6). The four types were

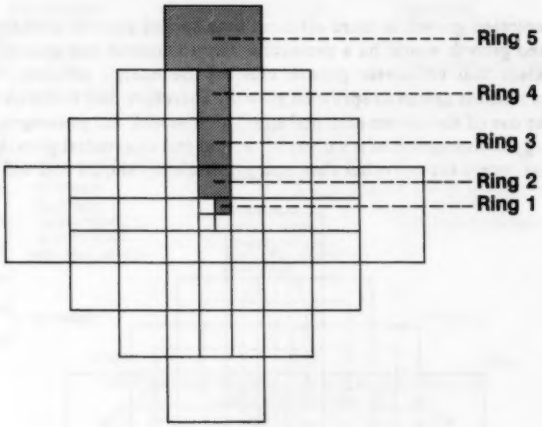

FIG. 6.—Alternative Cluster Locations

formed with basic employment, service (retail) employment, residences, and integrated developments at their foci. It is in the nature of the model, however, to allow some rearrangement of other (nonclustered) land uses in the city in response to the original nucleus. Thus, the basic employment cluster will tend to attract population and service employment around it, etc. This consequence is controlled by predefined work and shopping trip length preferences derived from other data, as well as the preestablished activity density constraints and attractor variables defined to produce a realistic base city.

Table 1 shows the cluster sizes tested; these were chosen to reflect the maximum initial, single cluster development sizes likely to be experienced in a city of 100–125,000, as determined from a review of recent development patterns, and the size of the total job market, in such cities. Other cluster sizes were tested, but their impacts exhibited no consistent size-related trend.

Results

Fig. 7 shows the relationship observed in the simulation model between distance of the nucleus from the CBD and energy consumption in passenger transportation for each cluster type (1 gal = 3.79 L). The standard incremental run (SIR), the simulation of the 25% growth increment with *no* policy change or further clustering of land use, is shown by the dashed line. It should be noted that, by virtue of the structure of the test city and the assumptions in the model, the SIR is a relatively centrally-oriented city. While the range of variation in fuel consumption across the options tested is small (±7%), the patterns of variation as a function of cluster type and location may have policy relevance.

Fig. 7 suggests that basic employment clusters are the least energy efficient of the three pure cluster types, although basic nuclei in rings 1 and 2 are slightly more efficient than the SIR. Residential and service employment clusters are similar to each other in terms of energy consumption patterns as a function of location, and both are more efficient than the basic employment clusters.

The overall development clusters produced by the initially-introduced basic employment nuclei were more extensive than residential and service employment

TABLE 1.—Approximate Cluster Sizes Tested

Cluster type (1)	Size (2)
Basic employment	1,500 Jobs
Service employment	1,500 Jobs
Residential	1,500 Residents
Integrated	1,000 Basic jobs; 1,000 Service jobs; 1,000 Residents

clusters because the model allows basic employment to affect the location of both residential and service activities. This effect is accentuated by the fact that trip cost preference functions permit simulated basic employment workers to make relatively longer trips to these large clusters. Thus, the off center, basic employment clusters introduced major, asymmetrical travel patterns into the city, with long trips and consequent increases in energy consumption. This effect was documented through analysis of zone-by-zone travel and location patterns simulated by the model system.

This interpretation is further reinforced by the observation that integrated clusters, dominated in their effects by the basic employment nuclei within them, were nearly as energy inefficient as the basic clusters themselves.

Analysis of zone-by-zone travel and locational patterns showed that off center basic employment clusters were less efficient because the trip length preference function allowed simulated travelers to make longer work trips to more distant clusters. That is, the noncentral basic employment clusters create an asymmetrical travel pattern, attracting long trips and consuming more energy.

The trip length (in vehicle-miles) impacts of residential and service employment clusters were smaller than for basic clusters. That is, these two types of nuclei had a more localized impact on travel and, furthermore, these two land uses

were mutually-reinforcing, creating well-defined, small, multiuse clusters which led to lower transportation energy consumption.

Fig. 7 also suggests that energy consumption climbs as the cluster moves outward from the center—or at least as it moves beyond ring 3. This was explained in terms of the asymmetrical character of "far" off center clusters, which create longer trip lengths and offer poorer markets for the CBD-oriented transit service. The clear decline in energy consumption for edge (ring 5) clusters is largely due to their location at the edge of the hypothetical city. Unlike a real city, the city in the model does not permit any development to occur past its outer edge. A growth nucleus at this boundary tends to be isolated because it is accessible only on one side; it attracts few trips and leads to less travel. In a real city, it can be expected that such an edge nucleus will

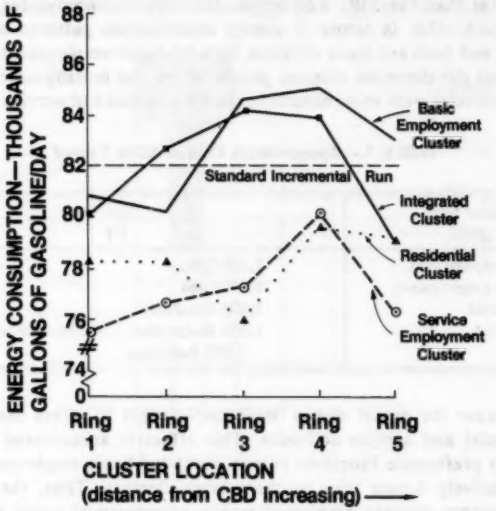

FIG. 7.—Energy Consumption for Passenger Transportation Versus Cluster Location

lead to more development in the hinterland of the city, increasing its spread and energy consumption as well. Thus, in reality, edge-development carries with it the serious risk of urban sprawl and ever-increasing transportation energy consumption.

The sharp decline in energy consumption when the residential cluster moves from ring 2 to ring 3 seems incongruous; further investigation, however, showed that this was an artifact of the population density constraints used in the model to ensure replication of a realistic city. That is, the density constraints served to keep residents away from the CBD to retain its employment character. When population clusters were tested in rings 1 and 2, only the predefined nuclei (1,500 people) was added, and the secondary clustering characteristics of other

cluster types, as illustrated by residential nuclei in rings 3–5, was precluded. When central area population density constraints were relaxed, and a modified standard incremental run simulated, which represents a centralized city, energy consumption dropped to the level indicated by #. in Fig. 7. This suggests a more logical pattern of energy consumption as a function of residential cluster location; energy consumption increases steadily with distance from the CBD up to ring 5. Accounting for the effects of *both* edge effects and central area density constraints, then, the hypothetical relationships between cluster location and passenger transportation energy consumption might be expected to take the form shown in Fig. 8. This suggests that, given the option, centralized growth nuclei are to be preferred to off center locations. Furthermore, "filling-in" the central area (rings 1–3) is preferred to encouraging growth beyond ring

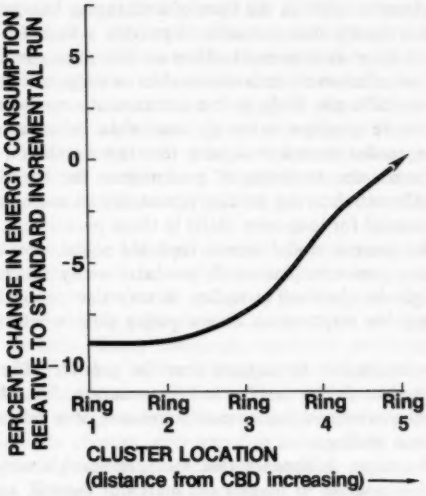

FIG. 8.—Hypothesized Relationship Between Cluster Location and Energy Consumption for Passenger Transportation

3. Such a policy may, indeed, be feasible in older cities where considerable vacant land and many obsolete structures exist in or near the core. Developments at the edge should probably be discouraged because of their effect on sprawl.

Where choices exist regarding the location of new basic employment, central locations seem even more strongly preferred, as basic clusters beyond ring 2 required more passenger transportation energy than the no-cluster standard incremental runs.

Conclusion

This research has demonstrated the use of aggregate computer simulation tools for exploring the passenger transportation energy consequences of various

urban development policies. There are clear limitations associated with this approach of which planners and policy makers must be aware. While many of these might be classified as technical details, the aggregate nature of the Lowry Model System utilized here merits further analysis.

All locators (e.g., households, employment opportunities) and potential locations (e.g., housing stock attributes and site amenities) are assumed in this model to be homogeneous. Thus, any household is assumed to be satisfied by the social and physical characteristics of any location in the city. Thus, location is determined primarily by travel costs and preferences, and to a lesser extent by density constraints and attractor variables specified to create a realistic SIR. Travel preferences are also assumed to be homogeneous across the population.

It seems quite possible for travel behavior parameters such as those used in this model system to shift in the face of a changing energy supply pattern. Although accepted theory does not exist to provide a basis for predicting such shifts, they could have an important effect on the phenomena treated in this research. Intuitively, however, it is reasonable to suggest that energy supply-driven behavioral shifts are likely in the intermediate run to make travel and location choices more sensitive to energy costs than indicated in this research. In any case, the reader should recognize that the simulation system used in this research ignores the variation of preferences for travel and locational attributes, and differentials in site bidding power, across socio-economic groups, as well as the potential for long-term shifts in these parameters.

As a result, the present model cannot replicate social, economic, and racial housing segregation patterns. This surely produces a city which is more energy efficient than might be observed in reality. It may also permit a greater degree of land use change in response to a new policy than would obtain in a real city.

It does seem reasonable to suggest that the *relative* efficacy of policies represented by the simulation results may be accurate. The absolute value of energy savings, however, and the cost-effectiveness of a particular policy, are not assured in these findings.

Ultimately, of course, it appears that there is enough variation in energy conservation across policies to suggest the merits of careful, analytically-based evaluation of development options—using more sophisticated, and locally-specific tools—in particular decision making contexts.

Given this warning regarding interpretation of the results, the following conclusions may be drawn. Centralized growth patterns appear to be relatively more attractive, in transportation energy consumption terms, than decentralized growth. Noncentralized growth nuclei are more energy consumptive than centralized growth nodes. Off center basic employment clusters are less attractive in this sense than decentralized residential and retail nuclei. While initial simulation work indicates that clusters at the edge of city lead to relatively lower energy consumption, it was concluded that this was an artifact of the modeling system; in reality edge nuclei should be avoided because of their serious and detrimental consequences for urban sprawl, which are likely to lead to increased per capita energy consumption.

The general principals derived from this research can be of immediate value to urban decision makers concerned with actions affecting contemporary de-

velopment proposals, such as zoning and building permits, public sector infrastructure investments, as well as decisions regarding the structure of metropolitan government. Specific actions and policies to implement, based on these principals, are necessarily the subject for local interpretation and assessment, because the simulation procedure does not, nor should it, specify them in detail. What follows are the action-oriented interpretations of the writers.

There appears to be clear merit associated with actions which encourage new development to be manifested as redevelopment of the core of the city; diversion of growth toward the center of the city can be expected to result in energy savings no matter what the energy economy characteristics of future transportation technology may be. This diversion may be accomplished through judicious use of zoning and building permit powers.

Similarly, investments in public infrastructure such as highways, transit services, and water and sewer lines should be directed toward increasing the attractiveness of the center city, rather than encouraging growth at the edge of a region. Furthermore, serious consideration should be given to the impact of the quality of public services and environmental attributes on urban location decisions. For example, to the extent that the quality of public schools influences the choice of home sites, which seems to be quite large, significant improvements in education may, in the long term, produce important transportation energy savings through urban form readjustment. Similarly, successful efforts to reduce central city crime rates may ultimately limit the growth of transportation energy consumption.

These interpretations suggest that efforts to limit transportation energy usage may need to be directed well beyond the transportation system itself. It is important for public decision makers to recognize that the performance of complex technological systems is highly dependent on many social and behavioral factors outside of those systems. Thus, seemingly unrelated decisions may, indeed, influence the energy efficiency of the urban transportation system itself.

Providing specific information to public decision makers, and individual locators themselves, about the energy consumption consequences of particular development proposals and site choices, may serve to increase the sensitivity of such actions to the options for energy conservation. This might be accomplished through requiring "Energy Impact Statements" to be prepared in support of development proposals just as Environmental Impact Statements are now a necessary part of certain (Federally-supported) projects. Consumers (individuals and firms) might be better informed in their choices through energy-cost labeling of sites in terms of their implied range of travel requirements.

Finally, it seems evident that one of the major obstacles to implementing policies of the type recommended here is the current structure of metropolitan government. The multiplicity of jurisdictions which make up regions, each largely funded through real estate, sales, and employment taxes, leads to decentralized decision making in which each general purpose government attempts to optimize its own financial future. This leads to intrajurisdictional competition for new growth, motivated by the desire of each separate government to capture the largest regional share of that growth. The result is a government-originated force toward decentralization, and thus a trend toward increasing energy consumption for urban passenger transportation (1).

An alternative, which recognizes the regional and national interest in energy

conservation, must be to bring governments together toward this end, through efforts to share regional decision making power and, more importantly, through a mechanism to share regional tax revenues for the betterment of the community as a whole.

Acknowledgment

This research was funded through the United States Department of Transportation, Research and Special Programs Administration, Office of University Research, Contract DOT-OS-50118. The opinions and conclusions expressed in this paper are those of the writers and do not necessarily represent the views of the United States Government.

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Fly Ash Sulfur Concrete

By William J. Head,[1] M. ASCE and Min-Fu Liao[2]

(Reviewed by the Highway Division)

Introduction

Waste product utilization is a topic of increasing concern to engineers and others responsible for environmental protection and energy conservation. Utilization enhances the environment by obviating waste disposal and promotes energy conservation by eliminating or reducing energy expended on raw materials processing.

Two "wastes" that can be combined to yield a potentially useful construction material are fly ash and elemental sulfur. This paper deals with laboratory development and characterization of mixtures of fly ash and elemental sulfur. Included is an assessment of potential utilization of the mixtures in a highway base course application.

Fly ash, a by-product of coal combustion, is a ubiquitous waste product particularly in the northeastern and midwestern portions of the United States. The great disparity between fly ash production and utilization is well-known. Approximately 48,300,000 tons (430 GN) of fly ash were produced in the United States in 1978 but only about 8,400,000 tons (75 GN) were utilized (1). Compounding the problem is the increase in the rate of fly ash production anticipated in the near future as newly constructed coal-fired electric generating stations commence operations and as existing oil and gas-fired facilities are converted to burn coal.

Presently, elemental sulfur is not a waste product; a semblance of balance exists between supply and demand. However, sulfur production is expected to increase dramatically during the next 20 yr due in large measure to the increasing reliance of the United States on sulfur-bearing coal as a major energy source. The effect of increased production is a projected sulfur surplus that is expected to exceed 15,000,000 tons (133 GN) by the year 2000 (4).

The purposes of this paper are: (1) To demonstrate that fly ash and sulfur can be combined to yield a potentially useful construction material; (2) to note

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on November 20, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0345/$01.00.

the strength parameters of selected mixtures; and (3) to assess the feasibility of utilizing the material in pavement construction. The work reported here was restricted in scope to attempts to mix fly ash and elemental sulfur to form hard, concrete-like substances termed fly ash sulfur concrete (FASC). Further, the scope was restricted to assessments of the potential utility of FASC as a highway pavement base course through use of a computer-based pavement performance simulation program. Finally, mixture durability was not addressed in this project.

The paper is divided into four parts. A technique for combining fly ash and sulfur in the laboratory to produce FASC is presented followed by characterization of mixtures with respect to selected strength parameters. Next, performance of two hypothetical highway pavements is assessed with the aid of a pavement performance simulation program. The base course of one pavement was a conventional crushed stone aggregate; FASC was the base course of the second pavement. Base course thicknesses, ambient temperatures, and subgrade support conditions were variables in the simulation program. Finally, relative base course costs are considered.

The production of FASC appears to be within the capabilities of existing technology. Development and utilization of FASC would both benefit the environment and promote energy conservation.

Laboratory Production of FASC

On the basis of work reported by McBee and Sullivan (5), heated fly ash, molten sulfur, and a modifying agent were mixed to produce a hard, concrete-like material, FASC.

The fly ash came from a coal-burning power station located near Morgantown, W.Va. Distribution of particle sizes in a sample of the ash is presented in Fig. 1. The average specific gravity of the fly ash is 2.26 and the average

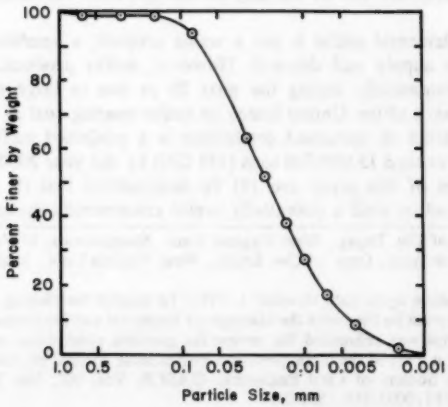

FIG. 1.—Fly Ash Particle Size Distribution

loss on ignition at 1,650° F (1,172° K) is about 3% (2).

The sulfur was commercial grade sulfur provided in flake form by a petroleum refining company. The purity of the sulfur was unknown but believed to be in excess of 99%.

The modifying agent was a technical grade of dicyclopentadiene, $(C_5H_6)_2$, supplied in liquid form. The assumed function of dicydopentadiene (DCPD)

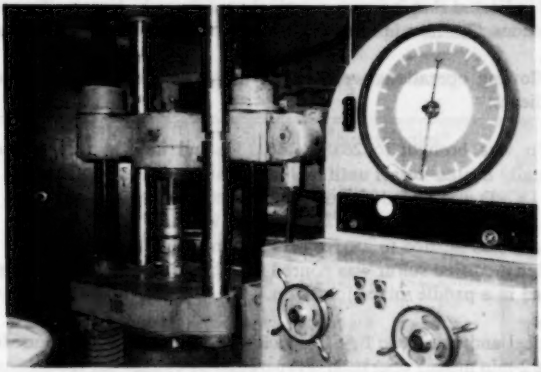

FIG. 2.—Cylindrical Specimen Fabrication Assembly

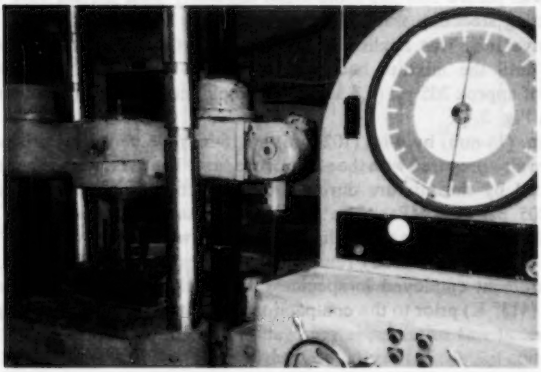

FIG. 3.—Prismatic Specimen Fabrication Assembly

was to inhibit the allotropic transformation of sulfur from the monoclinic crystalline form to the orthorhombic crystalline form (6). Neither the precise role of DCPD nor the transformation mechanism itself are well understood. Monoclinic sulfur forms above 204° F (369° K) and is the stable form at the melting point; approx 270° F (406° K). Orthorhombic sulfur is the most stable

form at room temperature. The mass density of orthorhombic sulfur, 2,070 kg/m^3, is significantly greater than the mass density of monoclinic sulfur, 1,960 kg/m^3 (6). Thus, sulfur cooled from the melt appears to have a structure that is vulnerable to disintegration upon exposure to stress inducing mechanisms such as thermal cycling (5). Consequently, the durability of unmodified sulfur-based materials subjected to weathering is questionable.

The DCPD was chosen as the modifying agent because results of other research programs indicated that it was a practical modifier which was effective in small concentrations (7). In addition, DCPD was relatively inexpensive and readily available.

The following operations were employed in the indicated sequence to mix the ingredients:

1. Sulfur was brought to 265° F (403° K) and held at that temperature in an electrically heated vessel until melting was complete.
2. The DCPD was added gradually while the mixture was stirred.
3. Mixture was maintained at 265° F (403° K) for 4 hr.
4. Fly ash was headed to 285° F (413° K) in a mixing bowl.
5. Molten modified sulfur was poured into the mixing bowl and the ingredients were mixed in a paddle mixer for 2 min.

Cylindrical and prismatic FASC specimens were fabricated immediately following the 2-min mixing operation. Preparation of cylindrical specimens involved fitting a 4-in. (102-mm) inside diameter by 8-in. (203-mm) high longitudinally split cylindrical steel mold with a 4.5-in. (114-mm) extension collar. The hot mixture was placed into the mold-collar assembly with the aid of a spoon and a tight-fitting steel cap was placed on top of the loose mixture. An increasing compressive load was applied to the cap with the aid of a universal testing machine until the mixture had been subjected to a maximum average axial pressure of approx 205 psi (1.4 MPa). The mold, collar, cap, and loading scheme appear in Fig. 2.

Three-in. (76-mm) by 4-in. (102-mm) by 16-in. (406-mm) long prismatic specimens were also prepared with the static procedure. The average maximum pressure experienced by the mixture during the compaction process was the same as before, 205 psi (1.4 MPa). The mold and pressure plate assembly is shown in place in the testing machine in Fig. 3. The two vertical rods visible in Fig. 3 served as handles for ready removal of the pressure plate from the mold.

All equipment employed in specimen fabrication was preheated in an oven at 285° F (413° K) prior to the compaction procedure. The purpose of preheating the equipment was to minimize segregation of sulfur in the molds.

Strength Characterization

Three tests were employed as aids in characterizing strength parameters of FASC. These were: (1) Unconfined compression test; (2) Splitting tension test; and (3) Flexure test.

Cylindrical specimens were tested in unconfined compression and splitting tension while the prismatic specimens were tested in flexure. All specimens were 7 days old at the time of test and all tests were conducted at room temperature.

Specimens were tested in unconfined compression according to the procedure specified in the American Society for Testing and Materials (ASTM) Standard Test Method C39. Test results appear in Table 1. The results indicate that strength is a function of mixture composition. Because modified sulfur serves as a bonding agent, a mixture with insufficient sulfur will be weak. Alternately, it appears that sulfur contents can be too great which also leads to reduced strength through a mechanism of excessive mixture shrinkage (7).

Although not clearly demonstrated in the results presented in Table 1, unconfined compressive strength is also affected by mixture unit weight. In

TABLE 1.—Strength Characteristics of FASC

Specimen Composition, as a percentage by weight			Average unit weight, in pounds per cubic foot	Strength Characteristics[a]			Modulus of Deformation, in 10^5 pounds per square inch	
				Unconfined compressive strength, in pounds per square inch	Splitting tensile strength, in pounds per square inch	Flexural strength, in pounds per square inch	In compression	In tension
Fly ash (1)	Sulfur (2)	DCPD (3)	(4)	(5)	(6)	(7)	(8)	(9)
65	20	10	102.1	264			1.1	
65	30	5	111.5	485			1.9	
70	24	6	110.3	890			2.4[d]	
70	27	3	117.7	1,159		555	4.0	4.2
70	27	3	109.5		198			
70	15	10	106.0	113			0.3	
75	20	5	108.5	954			2.2	
75	20	5	103.9[b]		158[b]			
75	20	5	112.3[c]			462[b]		2.0[c]
85	12	3	99.6	775			1.0	

[a] Average of two specimens unless otherwise noted.
[b] Four specimens.
[c] Three specimens.
[d] One specimen.
Note: 1 pcf = 0.157 kN/m^3; 1 psi = 0.0069 MPa.

preliminary tests conducted by the writers, increased unconfined compressive strength accompanied increased unit weight for mixtures of constant composition. Increased unit weight was the result of increased compactive effort.

The splitting tensile strength test was performed according to the procedure specified in ASTM Standard Test Method C496. The test was performed to assess the ability of FASC specimens to withstand tensile stresses.

Test results appear in Table 1 for two mixtures of different composition. Mixtures tested were the two which exhibited the highest unconfined compression strengths. Results again indicated that composition and unit weight affect mixture strength. In addition, it should be noted that for specimens of the same

composition, the ratio of splitting tensile strength to unconfined compression strength was approx 17%. This is similar to the magnitude of the corresponding ratio for Portland cement concrete which ranges between about 8% and 14% (8).

Specimens were tested in flexure according to procedures similar to those specified in ASTM Standard Test Method C78. Specimen span length was 14 in. (356 mm); the width of the specimens was 3 in. (76 mm); and the depth was 4 in. (102 mm). Test results appear in Table 1 for the same two mixtures employed in the splitting tension tests. As before, composition and unit weight affect strength. For specimens of the same composition, the ratio of flexural

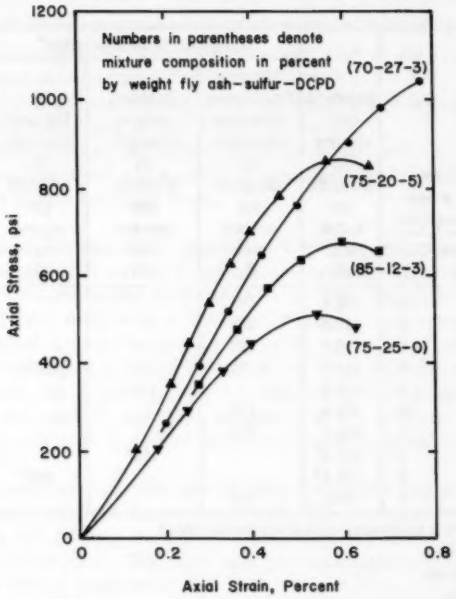

FIG. 4.—Axial Stress Versus Axial Strain to Rupture for Four FASC Mixtures

strength to unconfined compression strength is approx 48%. This is significantly greater than the magnitude of the corresponding ratio for Portland cement concrete which ranges between about 11% and 23% (8). Reasons for the large difference between the ratios for FASC and concrete are not known at this time.

Another characteristic of FASC appearing in Table 1 is the modulus of deformation which may be defined as the ratio of a stress to an appropriate strain. The modulus of deformation is an index of mechanical behavior of a material. Two procedures were employed in determining specimen moduli. Cylindrical specimens were loaded axially in compression in the first procedure. Both applied load and corresponding axial deformation were monitored until

the specimen failed. Failure occured when the specimen no longer sustained increasing load. Applied load was read directly from the testing machine; axial deformation was measured with the aid of a dial gage. Plots of average axial stress versus axial strain were made and points on the curves were located in which ordinates represented 50% of ultimate specimen strength. Values of axial stress so determined divided by the corresponding axial strain were designated the modulus of deformation for that sample. Representative stress-strain curves for four of the eight mixtures tested appear in Fig. 4. Prismatic specimens were tested in four-point bending in the second procedure. Applied load and maximum deflection were monitored as before, essentially to specimen fracture. Two mixtures were tested and load-deflection curves were plotted

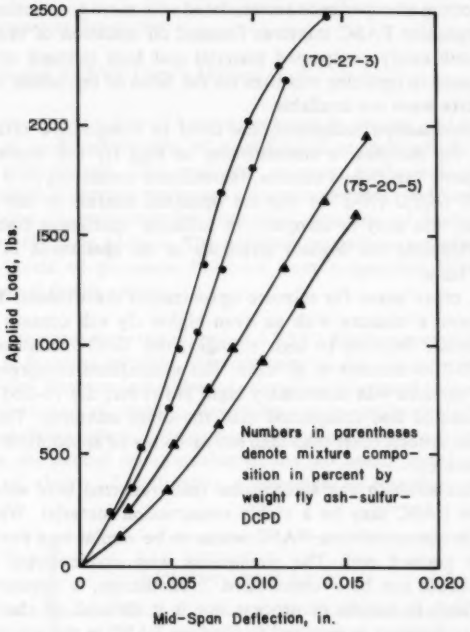

FIG. 5.—Load Versus Midspan Deflection for Two FASC Mixtures

for each test. Representative curves appear in Fig. 5. The following equation was used in calculating moduli values:

$$E = \frac{23Pl^3}{648I\Delta} \quad \ldots\ldots\ldots\

Numbers adjacent to each curve in Figs. 4 and 5 denote the mixture composition as a percentage of the total weight; e.g., "70-27-3" designates a mixture of 70% fly ash, 27% sulfur, and 3% DCPD by weight. Assessments of the curves indicate that the relationships between axial stress-axial strain and load-deflection are essentially linear almost to failure or almost to fracture, respectively. In addition, it is evident that both strain at failure and deflection at fracture were small. This behavior is typical of brittle materials. Moduli values in Table 1 appear to be affected by mixture composition and unit weight. The moduli values are similar in magnitude to values reported elsewhere for resilient moduli of Portland cement stabilized fine-grained soils (9). The modulus of deformation is not the same as the resilient modulus. Nevertheless, in at least a gross sense, this comparison of values serves to locate the modulus of deformation of FASC within the spectrum of experience accumulated with more conventional materials.

Efforts to optimize FASC mixtures focused on selection of mix proportions that yielded both easily compacted material and high strength specimens. No attempt was made to optimize mixtures on the basis of ingredient costs because reliable cost data were not available.

Given the compaction technique, the level of compactive effort employed in fabricating the samples, a committment to high fly ash content materials, and the previously mentioned criteria, the mixture containing 70% fly ash, 27% sulfur, and 3% DCPD (70-27-3) was the optimum mixture in this project. The 70-27-3 mixture was easy to compact. In addition, specimens frabricated from the mixture exhibited the highest strengths of all specimens in each of the three strength tests.

To be sure, other bases for mixture optimization are evident. For example, one might choose a mixture with an even higher fly ash content to maximize fly ash utilization. Relative to high strength, the 75-20-5 mixture was nearly the equal of 70-27-3 mixture in all tests. The unconfined compression strength of the 85-12-3 mixture was moderately high. However, the 70-27-3 mixture was more easily handled and compacted than the other mixtures. The intent here is to suggest that criteria other than high strength may be appropriate in optimizing mixture proportions.

Results of the strength characterization tests reported here substantiate the contention that FASC may be a viable construction material. With respect to certain strength characteristics, FASC seems to be similar to a Portland cement stabilized fine grained soil. The similarities with conventional materials of construction should not be overextended. Nonetheless, it appears that FASC is neither difficult to handle or process nor is it difficult to characterize. No extraordinary technology is required to produce FASC in the laboratory.

The magnitudes of the compressive, tensile, and flexural strengths of high fly ash content FASC are not particularly notable. However, the strengths are sufficient to warrant consideration of FASC as a candidate construction material for selected applications. One such application is utilization as a highway pavement base course material. The feasibility of utilizing FASC as a base course material is addressed in subsequent sections of this paper.

FASC as Highway Pavement Base Course Material

Assessments were made of the feasibility of utilizing FASC as a base course

material in flexible highway pavements. A base course application was chosen because of the large volume of ash potentially required in such construction and the general availability of fly ash in West Virginia and the surrounding region. A flexible highway pavement was chosen as the context for feasibility assessment because most highway pavements in West Virginia and many in the nation are flexible pavements. Finally, utilization of FASC as a flexible pavement base course was investigated because the Federal Highway administration (FHWA) made a computerized flexible pavement performance simulation program available to project personnel. The simulation program, VESYS IIM, provided both a means for rapidly reviewing effects of changes in base course type and thickness on predicted pavement performance and a uniform basis for comparing various pavements.

Pavement Performance Simulation

According to the VESYS User's Manual (3):

> . . . A pavement section of known geometry is chosen, and its behavior over time is predicted by sets of mechanistics models which have been computer programmed. The computer program package known as the VESYS System computes pavement response, distress, and serviceability. Results of the analysis must be compared with sets of decision criteria imposed by the user agency. The analysis process is repeated until the computed levels of pavement behavior over a specified lifetime, meet the established design criteria.

As noted in the preceding, the output of VESYS IIM is pavement performance predicted as a function of time. Performance is the combination of distress and serviceability. Distress is manifested as cracked pavement area and permanent longitudinal distortion or rutting. Pavement serviceability is indicated by the present serviceability index, a dimensionless number which reflects the public's assessment of the overall riding quality of the pavement. Serviceability ranges from a high of about 5.0, indicating a pavement of excellent riding quality,

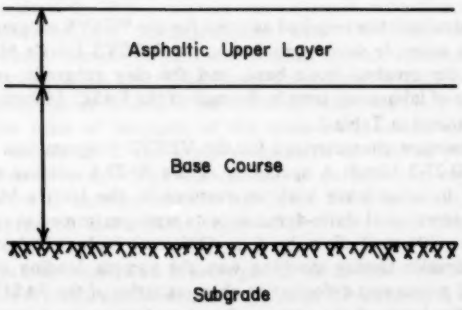

FIG. 6.—Three-Layer Flexible Pavement

TABLE 2.—Materials Characteristics

Material (1)	CREEP COMPLIANCE, in 10^{-6} inches per inch: Time When Creep Compliance was 0.001 (2)	0.003 (3)	0.02 (4)	0.1 (5)	0.3 (6)	1 (7)
Asphalt layer	0.37	0.52	0.86	0.14	2.5	4.0
Crushed stone	17	17	17	17	17	17
FASC	2.5	2.5	2.5	2.5	2.5	2.5
Clay subgrade, 16% water content	22	22	22	22	22	22
Clay subgrade, 23% water content	200	210	220	240	280	330

*Definitions and instructions for calculating creep compliance and permanent deformation

Note: 1 (in./in.)/psi = 145 (mm/mm)/MPa.

to a low of 0.0, indicating a pavement with extremely poor quality riding characteristics. A serviceability of 2.5 is commonly assumed to be the terminal serviceability for a "high-type" pavement; i.e., a United States primary or interstate system highway pavement. Pavements with a lower serviceability are generally assumed to require corrective measures, such as an overlay layer, to raise the riding quality of the pavement to acceptable levels.

The performance of three-layer flexible pavements can be simulated with the VESYS IIM program. Fig. 6 is a schematic representation of a three-layer flexible pavement. Characteristics of the asphaltic upper layer, the base course, the subgrade, and thicknesses of the upper layer and base course can all be varied. Additional program variables are average temperature of the environment, traffic loading, and pavement serviceability limits.

Materials Characterization

Materials characteristics required as input for the VESYS program were either taken from the example design problem in the VESYS User's Manual for the asphalt layer, the crushed stone base, and the clay subgrade, or determined from the results of laboratory tests in the case of the FASC. Material characteristics are summarized in Table 2.

The FASC mixture characterized for the VESYS program was the optimum mixture, the 70-27-3 blend. A specimen of the 70-27-3 mixture was tested in the laboratory in accordance with instructions in the User's Manual. Direct compression, incremental static-dynamic tests were performed at room temperature on a 4-in. (101-mm) diam by 8-in. (203-mm) high cylindrical specimen. An electro-hydraulic testing machine was the sample loading device. Creep compliance and permanent deformation characteristics of the FASC sample were calculated on the basis of the test results according to the instructions in the Manual. Values are recorded in Table 2 along with values of the same parameters

for VESYS Program*

per pounds per square inch Determined, in seconds					Permanent Deformation Characteristics	
3 (8)	10 (9)	30 (10)	100 (11)	1,000 (12)	Gnu (13)	Alpha (14)
6.2	8.6	12	16	19	0.318	0.756
17	17	17	17	17	0.055	0.730
2.5	2.5	2.5	2.5	2.5	0	1
22	22	22	22	22	0.0075	0.850
400	450	500	550	600	0.0357	0.643

characteristics are found in Ref. 3.

for the asphalt layer, the crushed stone base material, and the clay subgrade at the two water contents, 16% and 23%.

It should be noted that the creep compliance values are arrayed in Table 2 in the order they are input into the VESYS program. The crushed stone, FASC, and the drier (16% water content), clay subgrade all exhibited constant values of creep compliance. This behavior is characteristic of elastic materials. However, both the crushed stone and the drier subgrade material experienced permanent deformation during the repeated load portion of the characterization test as evidenced by the values of the permanent deformation parameters, Gnu and Alpha, for these materials appearing in Table 2. The FASC, on the other hand, exhibited no detectable permanent deformation after 100,000 load applications. Consequently, the values of Gnu and Alpha for FASC are zero and one, respectively. Definitions of Gnu and Alpha and techniques for evaluating them are found in the VESYS User's Manual.

Only one sample of the 70-27-3 mixture was subjected to the direct compression, incremental static-dynamic characterization tests. However, the sample did behave in an elastic manner in the tests. Thus, it appears reasonable to assume that the reciprocal of the calculated creep compliance should be of the same order of magnitude as the moduli of deformation determined in previous strength characterization tests of mixtures of the same composition and similar unit weights. The reciprocal of the creep compliance is 400,000 psi (2,758 MPa) which compares favorably with the moduli of deformation reported for the mixture in Table 1, namely, 400,000 psi (2,758 MPa) and 420,000 psi (2,896 MPa) in compression and flexure, respectively. The very small differences between the three moduli are fortuitous. Nevertheless, the good agreement between values was considered at least partial justification for testing only one specimen in the VESYS characterization process. In addition, it was recognized that the thrust of the feasibility/performance comparison effort was not to determine definitive FASC characteristics but rather simply to demonstrate the

potential viability of FASC as a construction material. Results from one carefully conducted test, bolstered by results from other independent tests, were sufficient for that purpose in the judgement of the writers.

Procedure

Predicted performance of numerous hypothetical flexible pavement systems were analyzed and compared to assess the feasibility of utilizing FASC as a base course material. The pavement systems considered are listed in Table 3. Of the 74 flexible pavements analyzed, 40 had crushed stone base courses and 34 had FASC base courses.

TABLE 3.—Pavement Systems in VESYS Comparisons

System designation (1)	Range of total thickness of upper layer, in inches (2)	Base Course		Water content of clay subgrade, as a percentage (5)	Temperature array (6)
		Type (3)	Range of thickness, in inches (4)		
A	2–8	Crushed stone	4–10	16	Vum
B	2–12	Crushed stone	4–24	23	Vum
C	2–8	FASC	4–10	16	Vum
D	4–8	FASC	6–18	23	Vum
E	2–8	Crushed stone	8	16	Mgt
F	10	Crushed stone	24	23	Mgt
G	2–8	FASC	8	16	Mgt
H	4	FASC	6–12	23	Mgt

Note: 1 in. = 25.4 mm.

TABLE 4.—Temperature Arrays in VESYS Comparisons

Temperature array (1)	Average Monthly Temperature, in degrees Fahrenheit											
	January (2)	February (3)	March (4)	April (5)	May (6)	June (7)	July (8)	August (9)	September (10)	October (11)	November (12)	December (13)
Vum	49.7	53.3	59.5	68.6	75.2	81.6	84.6	84.7	78.9	70.1	59.1	52.3
Mgt	28.3	30.7	41.4	51.2	54.9	68.0	71.7	70.8	65.4	52.8	44.2	35.2

Note. 1° F = 1.8 K − 460.

Two subgrade conditions were employed in the analyses; the first was the 16% water content condition where the assumed clay subgrade was stiff and essentially elastic in nature. The second was the 23% water content condition where the clay subgrade was relatively weak and viscoelastic in nature. Two monthly temperature arrays were employed: (1) The first array, taken from

the User's Manual and designated Vum, represented a relatively warm climate; and (2) the second and cooler climate array, Mgt, represented the mean monthly temperatures for the Morgantown, W.Va. area over the 10-yr period 1970–1979 (Table 4).

Traffic conditions adopted in the comparisons were the same as those noted in the example design problem in the User's Manual. In brief, the average daily heavy truck traffic varied from about 670 to about 1,000 over the selected 20-yr analysis period while the average numbers of axles per truck varied from three to four during the same period. Details of the traffic analysis are found in the Manual.

The ranges of asphalt layer and base course thicknesses employed in the comparisons were chosen to represent practical values for layers found in highway pavements. Exceptions were systems B, D, and F where very thick pavements were analyzed to ascertain if any sections were feasible for the imposed conditions.

Criteria

The serviceability criteria adopted in comparing pavement systems were essentially the same as those noted in the example design problem in the User's Manual; viz., terminal serviceability index of 2.5, less than 500 sq yd (418 m^2) of cracking per 1,000 sq yd (836 m^2) of pavement surface in 20 yr, less than 0.50 in. (13 mm) of rut depth in 20 yr, and less than 10×10^{-6} rad of slope variance in 20 yr. Slope variance is a measure of pavement roughness, i.e., short wave length pavement distortion.

An additional criterion was that the damage index should be as small as possible but in no case larger than 1.0. The damage index is a measure of the probability that a given pavement system will experience cracking. A value of 1.0 or more indicates that the system will crack. This criterion was adopted upon the recommendation of personnel who were instrumental in developing the VESYS program.

Results and Review

Results of VESYS analyses of selected crushed stone and FASC base course pavement systems appear in Table 5.

It is evident that performance of FASC base systems is superior to performance of the crushed stone base systems when comparisons are made between pavements with equal thicknesses of like layers. Alternately, for two systems with the same upper layer thickness, equal pavement performance is predicted when the thickness of the FASC base course is less than the thickness of the crushed stone base course.

The severity of the 23% water content subgrade condition should be noted. No satisfactory pavement section was found for this condition when the base course material was crushed stone and the warm temperature array, Vum, was considered. For the same conditions, it appears that an adequately performing section could consist of a 4-in. (102-mm) thick asphaltic upper layer and a 14-in. (356-mm) thick FASC base course. Good pavement design and construction practice would focus on eliminating or avoiding the unfavorable subgrade conditions, or both. Nevertheless, the VESYS analysis demonstrates that the

TABLE 5.—Pavement Performance Predicted by VESYS Analysis

Base course (1)	Temperature array[a] (2)	Subgrade water content, as a percentage (3)	Thickness of upper layer, in inches (4)	Thickness of base course, in inches (5)	Rut depth, in inches (6)	Slope variance, in 10^{-6} radians (7)	Damage index (8)	Cracking, in square yards per 1,000 sq yd of surface (9)	Serviceability at 20 yr (10)	Pavement life,[b] in years (11)
Crushed stone	Vum	16	4	6	0.19	1.2	2.3	1,000	3.8	>20
			4	8	0.20	1.2	2.2	1,000	3.8	>20
			4	10	0.20	1.1	2.2	1,000	3.8	>20
			6	6	0.24	2.1	0.81	0	3.9	>20
			6	8	0.25	2.1	0.79	0	3.8	>20
			6	10	0.25	2.0	0.78	0	3.9	>20
			8	8	0.25	2.2	0.33	0	3.8	>20
			8	10	0.26	2.1	0.32	0	3.8	>20
Crushed stone	Vum	23	4	6	1.5	60	5.3	1,000	<1	1.0
			4	8	1.3	43	4.2	1,000	<1	1.9
			4	10	1.1	29	3.5	1,000	<1	3.5
			6	6	1.3	53	1.8	1,000	<1	1.6
			6	8	1.2	40	1.5	1,000	<1	2.2
			6	10	1.1	30	1.3	1,000	<1	3.4
			8	8	1.0	34	0.60	0	<1	3.0
			8	10	0.95	27	0.54	0	<1	4.5
			10	10	0.90	26	0.25	0	<1	5.1
			10	14	0.81	19	0.21	0	1.5	7.4
			10	18	0.72	14	0.19	0	1.9	11
			10	22	0.65	11	0.17	0	2.2	15
			10	24	0.63	9.8	0.16	0	2.3	17
			12	14	0.79	19	0.11	0	1.5	7.6
			12	18	0.72	15	0.09	0	1.9	11
			12	22	0.69	13	0.09	0	2.0	12
			12	24	0.64	11	0.08	0	2.3	16
FASC	Vum	16	4	6	0.13	0.49	0.27	0	4.5	>20
			4	8	0.12	0.41	0.21	0	4.5	>20
			4	10	0.12	0.32	0.18	0	4.6	>20
			6	6	0.19	1.1	0.14	0	4.2	>20
			6	8	0.18	0.99	0.12	0	4.2	>20
			6	10	0.18	0.86	0.10	0	4.3	>20
			8	8	0.20	1.2	0.06	0	4.1	>20
			8	10	0.19	1.1	0.05	0	4.2	>20
FASC	Vum	23	4	10	0.57	10	0.20	0	2.4	19
			4	12	0.52	9.6	0.17	0	2.6	20
			4	14	0.49	9.2	0.16	0	2.6	>20
			4	18	0.46	9.0	0.15	0	2.7	>20
			6	6	0.89	20	0.25	0	1.2	6.4
			6	8	0.72	12	0.17	0	2.0	12
			6	10	0.60	9.5	0.13	0	2.4	19
			6	12	0.52	7.7	0.10	0	2.7	>20
			6	14	0.47	6.7	0.09	0	2.9	>20
			6	18	0.42	5.6	0.08	0	3.0	>20
			8	8	0.72	12	0.09	0	1.9	12
			8	10	0.61	9.9	0.07	0	2.4	19
			8	12	0.53	7.4	0.06	0	2.7	>20
			8	14	0.48	6.2	0.05	0	2.9	>20
			8	18	0.42	5.0	0.04	0	3.2	>20

TABLE 5.—*Continued*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Crushed stone	Mgt	16	4	8	0.15	0.71	1.2	973	4.0	>20
			6	8	0.17	1.0	0.32	0	4.2	>20
			8	8	0.16	0.91	0.11	0	4.3	>20
Crushed stone	Mgt	23	10	24	0.41	4.2	0.07	0	3.3	>20
FASC	Mgt	16	4	8	0.11	0.31	0.19	0	4.6	>20
			6	8	0.14	0.62	0.09	0	4.4	>20
			8	8	0.15	0.66	0.04		4.4	>20
FASC	Mgt	23	4	6	0.59	9.4	0.42	0	2.4	19
			4	8	0.48	6.7	0.26	0	2.9	>20
			4	10	0.42	5.8	0.19	0	3.1	>20
			4	12	0.40	5.5	0.16	0	3.1	>20

[a]Arrays are found in Table 4.
[b]Approximate time for serviceability to reach 2.5.
Note: 1 in. = 25.4 mm.

crushed stone, as characterized in Table 2, is simply not a suitable base course material for certain conditions.

The superior predicted performance of pavement systems with FASC bases is attributable to the greater stiffness of FASC compared to the crushed stone. High stiffness was a desirable base course characteristic for the problems analyzed with the aid of the VESYS program in this paper. However, high base course stiffness is not de rigueur in the design of all highway pavements. To the extent possible, the competent pavement designer will tailor available materials and construction processes to specific conditions and needs which may or may not require a high stiffness base course.

Finally, the purpose of the analyses and comparisons should be reiterated; viz., to demonstrate potential viability of FASC as a construction material. In the writers' judgements, that goal has been achieved in at least a theoretical sense. For selected conditions and from the standpoint of predicted highway pavement performance, FASC appears to be superior to a conventional crushed stone material when utilized in a base course application.

Relative Costs

No demonstration of potential material viability is complete without an assessment of costs. Unfortunately, realistic cost estimates for FASC are not available. However, certain comparative cost information can be examined which may serve to place the viability issue in perspective.

The in-place cost of a base course is given by:

$$\text{In-place cost of base course} = C\beta LWT \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which C = cost per unit weight of base course material in-place; β = unit weight of base course material in-place; L = length of base course; W = width of base course; and T = thickness of base course. Equating costs of a crushed stone and a FASC base course:

$$(C\beta LWT)_S = (C\beta LWT)_F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which S denotes crushed stone; and F denotes FASC. Assuming equal section lengths and widths and assuming approximately equal in-place unit weights:

$$C_F \simeq C_S \frac{T_S}{T_F} \quad \ldots\ldots\ldots\

specimens of FASC noted earlier in this paper indicates a potential upper boundary for the cost issue. The fabrication experience suggests the possibility of employing essentially traditional hot-mixed asphaltic concrete technology for mixing and placing FASC. Consequently, it is conceivable that the in-place cost of FASC might be no more than the in-place cost of asphaltic concrete which is, e.g., about $35/ton in the Morgantown, W.Va. area according to an estimate supplied by a local paving company in Sept., 1980. Thus, FASC may be an economically viable highway pavement base course candidate in the Morgantown area given the foregoing assumptions, a favorable base course thickness ratio, and an in-place cost approaching that of asphaltic concrete. Obviously, "economic viability" is strongly affected by the base course thickness ratio. Reasonably accurate and reliable estimates of thickness ratio values are a prerequisite of realistic economic assessment of FASC or any other candidate base course material.

Durability

Another criterion of material viability is durability. FASC must be durable both with respect to freezing and thawing and with respect to wetting and drying in highway base course applications. The durability of FASC is unknown at this time. Studies are currently underway to assess FASC durability.

Future Applications

The thrust of this paper was to demonstrate that FASC is a viable construction material. Clearly, the demonstration is incomplete when cost and durability data and construction experience are lacking. Nevertheless, a substantial case has been made for the possibility of utilizing waste products in construction. A major implication of this paper for future design and construction is that waste products, either singly or in combination with other wastes/stabilizing agents, can and should be considered as candidate construction materials along with more conventional and traditional materials. The advent of advanced analytical procedures, such as the VESYS IIM program, and materials characterization techniques make such considerations tractable.

Summary and Conclusions

It is shown in the work reported here that fly ash and elemental sulfur can be combined with a suitable modifying agent to produce a hard substance termed fly ash sulfur concrete (FASC). The technology required to fabricate specimens of FASC in the laboratory is similar to and no more complicated than the technology employed in fabricating specimens of hot-mix asphaltic concrete. Strength characteristics of FASC are functions of the amounts of the ingredients present and the unit weight of the mixture. Moduli values are similar in magnitude to values reported for Portland cement stabilized fine-grained soils.

When compared with a conventional crushed stone material, FASC is a viable highway pavement base course candidate from the standpoint of predicted theoretical pavement performance. Definitive assessments of the utility of FASC await the development of reliable cost and durability data and the acquisition of construction experience.

Acknowledgments

The writers wish to acknowledge the support of both the West Virginia University Energy Research Center which funded research project ST 80-20 on which this paper is based and the materials and Control Division of the West Virginia Department of Highways which supplied certain equipment to the project. The writers wish to thank Mr. W. J. Kenis of the FHWA who supplied the VESYS IIM program to the project. Finally, the writers wish to thank K. C. Keith, H. M. Phillippi, and Susan Cowger for their assistance.

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Appendix II.—Notation

The following symbols are used in this paper:

C = cost per unit weight of base course material in-place;
DCPD = dicyclopentadiene;
E = modulus of deformation;
FASC = fly ash sulfur concrete;
I = moment of inertia;
L = length of base course;
l = span length;
Mgt = cool climate mean monthly temperature array;
P = applied load;
T = thickness of base course;
Vum = warm climate mean monthly temperature array;

W = width of base course;
w = water content;
β = unit weight of base course material in-place; and
Δ = midspan deflection.

Subscripts

F = fly ash sulfur concrete; and
S = crushed stone.

TAPS Design Concepts: Environmental Concerns[a]

By Morris J. Turner,[1] F. ASCE

(Reviewed by the Pipeline Division)

Introduction

Today, in relative harmony with the environment, the Trans-Alaska Pipeline System (TAPS) is transporting crude oil for our energy deficient nation. The 48-in. (122-cm) diameter pipeline stretches 800 miles (1,287 km) from Prudhoe Bay to Valdez. Filled, the line holds some nine million barrels (1.43 million m^3) of crude—an inventory in itself worth over 250 million dollars. The system contains 151 mainline valves, nine operational pump stations with an additional station providing draindown capability on the south side of the Brooks Mountain Range, and a terminal at the ice-free Port of Valdez.

Currently, the project has a throughput of 1.5 million barrels (238,000 m^3) per day. The system capability with the addition of three more operating stations would be two million barrels (318,000 m^3) per day.

The terminal consists of a sophisticated communication and control system, storage tanks, a vapor recovery and ballast water treatment system, and port loading facilities.

Additionally, sophisticated facilities exist at the oil field at Prudhoe Bay as well as the marine leg which transports crude oil from Valdez, Alaska, to refineries in the "lower 48." These facilities also represent great engineering feats. Over 25 billion dollars have been spent in this endeavor.

Builders of future pipeline or other large civil engineering projects in northern latitudes will benefit from the extensive experience gained by Alyeska Pipeline Service Company (APSC). [Company formed by TAPS Owners (Amerada Hess Pipeline Corporation; ARCO Pipe Line Company; BP Pipelines Inc.; Exxon Pipeline Company; Mobil Alaska Pipeline Company; Phillips Alaska Pipeline Corporation; Sohio Pipe Line Company; Union Alaska Pipeline Company) to be common agent responsible for the design, construction, and operation of

[a]Presented at the April 14–18, 1980, ASCE Convention and Exposition held at Portland, Ore.

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Note.—Discussion open until October 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on April 3, 1980. This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0365/$01.00.

the pipeline project.] The experience gained on TAPS should be used to improve future systems designed to provide transportation without undue environmental consequences. This can be done by incorporating the necessary engineering, construction, and operational constraints into the design at an early stage so as to minimize environmental impacts.

This paper describes some of the design concepts employed to provide an operational facility which would be environmentally acceptable in today's world. Because of the large scope of the project, the review presented herein treats only the major design concepts in a very general way since detailed examination of most any feature would in itself require a paper-length presentation.

Significance of Trans-Alaska Pipeline Project

Until June 1977 when TAPS started operations, 32% of the known remaining petroleum reserve of this country was contained in an area of about 300 sq miles (7.77 km^2) on the North Slope of Alaska, an area smaller than Portland, Oregon, and its suburbs. The Prudhoe Bay oil field contained some 9.8 billion barrels (1.56 billion m^3) of recoverable crude oil and 26 trillion cu ft (0.736 trillion m^3) of natural gas in one producing geological formation. Today 1.35 billion barrels (216 million m^3) of crude oil have been transported through TAPS. It is obvious that the Prudhoe Bay oil field, TAPS, and the marine leg are not only critical to the daily supply of crude oil for this country, but to the country's overall economic stability.

Fundamental Concerns

The pipeline right-of-way transects many different physiographic zones where little or no baseline data was heretofore available. Each of these regions posed different construction and environmental obstacles. Probably the most important aspect of the Alaskan environment as it relates to design and construction is permafrost. Permafrost is a temperature condition of the soil. It is defined to exist when the soil temperature is at or less than 32° F (0° C) continually for 2 yr or more (13). This condition is prevalent over much of the pipeline route.

An overriding consideration in much of the design for the TAPS involves building and operating a hot oil pipeline in ice-rich thaw-unstable soils (1). Failure to accommodate this phenomena can have significant environmental impacts resulting from surface disturbance through thermal and water erosion. Likewise, in a climatic and geographic setting such as Alaska, major terrain disturbance of fish and wildlife habitat and natural terrain often take generations in time to heal, if ever. Yet, the tools are available for the engineer today to do his job timely, economically, and environmentally.

Many of the project concerns during design and construction centered around:

1. The protection of the sensitive permafrost from excessive erosion.
2. Prevention of excessive deformation (from mass wasting and seismic conditions).
3. Assurance of safe fish and wildlife passage across the pipeline route and protection of endangered species.

4. Abatement of pollution, such as waste water, solid waste disposal, and air quality.
5. Minimization of area disturbances and material utilization, such as gravel for roads and camp facilities.

These basic project concerns were to ensure that pipeline integrity was maintained and that the project would cause minimal disturbance to the natural environment.

Environmental Impact (10,15)

Defining the levels of environmental impact associated with TAPS is difficult for two reasons. Although impacts are real, many types cannot be readily described in terms of quantifiable parameters in the manner in which engineering problems are defined. In addition, most of the biological survey work performed in advance of construction was descriptive and there is a relative scarcity of background data from which to compare post-construction and operational effects. Most environmental concerns address protection either in terms of minimizing effects or adhering to State and Federal regulations or permit requirements. Because of these factors, an analysis of environmental impacts is by necessity qualitative, and it is seldom possible to determine the degree of the environmental effects that actually occurred (12).

Rather than presenting a detailed discussion of specific environmental impacts, such as oil spills, this paper considers the design concepts used to control and prevent such impacts during operation of TAPS.

Design Decisions

Construction of TAPS was authorized by Congress in November 1973 (19). Project mobilization commenced in February 1974 (1), with main pipeline field work (not support facilities or fabrication of pipeline subsystems) starting in March 1975, only a little over a year after final legal obstacles were overcome (1). The project was put into operation a little over 2 yr later on June 20, 1977.

While the mainline pipe had been purchased in 1969, other project decisions were not forthcoming until 1974. Consequently, numerous hard design decisions had to be made in early 1974 to enable manufacturing and delivery of the system components in time for construction, a condition all too familiar to the practicing engineers. In this case, these decisions ultimately not only required concurrence by the project owners but also subsequently by the Government whose primary concerns were about the environmental impacts associated with the project.

Construction Facilities and Systems

A full appreciation of the design concepts used to minimize environmental concerns is not possible without a feel for some of the significant aspects of the construction phase of TAPS.

Mobilization.—Concurrent with signing of the permit to construct TAPS (1,19),

APSC mobilized north of the Yukon River across ice bridges, over snow roads, and by air. They established base camps; semipermanent (year-round) airfields; petrol, oil and lubricants (POL); and equipment pools, all generally during a period of about 80 days. For example, 900,000 gal (3,420 m^3) of diesel fuel (400,000 by road and 500,000 by air), 600 tons (540 MT) of replacement parts, and 600 prefabricated buildings were delivered. This mobilization effort was accomplished in temperatures down to −68° F (−56° C) across the frozen North, yet, it could not have been accomplished in this time frame it it had not been for the winter season (15). Conventional roads, bridges, and airstrips require more time to build than snow roads, ice bridges, and airstrips on frozen lakes or rivers.

Routes of Communication.—Before construction of the pipeline commenced, Alyeska determined it was necessary to construct a 395-mile (636-km) long, 28-ft (8.5-m) road between Prudhoe Bay and Livengood for the movement of pipeline construction material and pipeline and oil field operations (8). Routing of the road generally parallels the hot oil pipeline alignment. It is the first all-weather highway to be built north across the Arctic Circle in the United States. The Haul Road was designed to disturb the terrain as little as possible. On stable subgrade soil, the road has a 3-ft (1-m) gravel base; on less stable soil, the base is from 5 ft–6 ft (1.5 m–1.8 m) thick. An average of 110,000 cu yd (84,095 m^3) of gravel was moved each day making it possible to complete the portion of the road from the Yukon River to Prudhoe Bay in only five months. Some 23,120,270 cu yd (17,675,446 m^3) were used in constructing this portion of the highway (8).

Additionally, Alyeska designed and built ten operational airfields for fixed-wing aircraft and a permanent bridge across the Yukon River to support their construction efforts.

Construction Camps.—A total of 29 self-contained construction camps with full facilities to house approximately 22,000 workers were used during the TAPS project. These camps, each virtually a small city in itself, were located at strategic locations along the pipeline right-of-way, at the pump stations, and the terminal.

Construction Systems.—Manufacturers and engineering firms combined their talents in pioneering Arctic construction technology through specially built systems to assist in the construction effort. Some, but by no means all, of the equipment that was designed to meet Arctic conditions while assisting in minimizing the environmental impacts were:

1. Air-Cushioned Transporters: Two air-cushioned transporters designed to handle cargo loads up to 160 t (145 MT) were capable of making one-way 5,000-ft (1,524-m) trips across the Yukon River in about 15 min. These transports were used before completion of the Yukon River Bridge and during periods when an ice bridge across the river could not be used.
2. Aboveground Pipe Insulating System: To install one piece of composite fibrous glass material, factory-bonded to a galvanized steel outer jacket, three pieces of special equipment were used. A vacuum lift mandrel handler, a strait panel unfolder, and a vacuum manipulator.
3. Rock Saws: An endless cutter chain with carbide tipped teeth attached to the back of a D-9H Caterpillar was used in trenching portions of the line.

This 125,000-lb (56,700-kg) machine cuts a 12-in. (0.3-m) wide slot to a depth of 8 ft (2.44 m).

4. Drill Rigs: Rigs were designed and built to predrill some 78,000 vertical support member pilings. The rigs used specially designed drills, rotary heads, and interchangeable bits. Some of these rigs weighed 100 tons (90 MT).

5. Elevating System Platform (ESP): A tractor was custom engineered specifically for work on aboveground portions of TAPS. It is a self-contained, all-terrain mobile unit with two independently operable extendable work platforms.

6. Internal Inspection/Weld Vehicle (Snoopy): Snoopy is a self-contained vehicle to inspect and repair interior weld joints. The vehicle is operated by an onboard crew member who visually locates the weld joint while traveling within the pipe. Snoopy moves through the pipe at 3 mph (4.8 km/h), negotiating 23-degree horizontal bends as well as 35-degree or less sag bends and overbends.

Numerous other systems such as pipe corrugators, grouting units, aerial tramways, aerial basket lifts, semiautomatic welders, ditching machines, pipe benders, and pipe heaters were designed and used in construction of TAPS. The intent of this limited presentation is to focus on not only the operational designs but the total engineering systems associated with construction and operation of TAPS.

Project Design Features

To minimize the potential environmental impact, considerable care was taken in the design of the various project features. The ensuing review describes some of the more noteworthy aspects of some of the TAPS features.

Pipeline.—The following are characteristics of the pipeline.

Pipe.—Soil and service conditions in Alaska have presented unusual challenges to designers of the line. In the coldest regions, the permafrost is close to the surface and is covered by a thin seasonal freeze-thaw layer and surface vegetation—the tundra. This serves as insulation limiting permafrost thaw in the summer. It is easily damaged, causing a reduction of its insulating values with resultant melting of the permafrost (18). In thaw-unstable soils, this can be disastrous. Therefore, special construction designs and techniques had to be developed to protect these permafrost and seismic active areas.

The pipe was specially engineered and fabricated for the Arctic environment. The steel used (6) met and exceeded ANSI B31.4 (11,20) and API line pipe standards for X-60, X-65, and X-70 pipe. The pipe was produced in two wall thickness of 0.462 in. and 0.562 in. (1.17 cm and 1.43 cm). The steel was manufactured to provide ductile pipe with high impact properties (7) even at −40° F (−40° C). While the pipe will generally not be subjected to unusual forces during operation, the pipeline was designed to sustain all expected hydraulic pressures, thermal forces, and stress induced by settlement, compaction, earthquakes, and weight between supports of the elevated line as well as the construction associated problems. Different grades of pipe were used in different locations depending on the pressure and stress in each location.

Elevated.—The throughput of oil in the pipeline from Prudhoe Bay remains warm enough [approx 140° F (60° C)] to alter the thermal regime of critical permafrost areas if in a buried mode. To prevent the degradation of thaw-unstable

permafrost, portions of the pipeline route are elevated for approx 433 m (697 km) so that at least 24 in. (61 cm) of separation between the pipe and ground surface exists. Warm oil is less viscous and, therefore, requires less energy to move along the pipeline so the elevated pipeline mode is also insulated to retain its heat to save pumping costs.

With insulation there are some secondary benefits, such as physical protection of the mainline pipe and a reduction in thermal transfer from the warm pipe to the ground. The pipe is covered with 4-in. (10-cm) thick fiberglas insulation panels with a sheet metal outer shell wrapped and riveted at a lap. The support clamps at intermediate slide shoe and clamps at anchor assemblies are covered with prefabricated insulation modules. These modules are rigid foam insulation enclosed in a fiberglas reinforced plastic shell. The mainline valves in the aboveground portion of the line were also insulated by field application of rigid foam and protective covering. Each transition section, where the pipe either enters or comes out of the ground, has a rigid insulation covering protected by a waterproof plastic outer shell.

An elevated pipeline presents a number of problems not associated with a totally restrained, buried line. Provision must be made to allow for the forces generated by thermal expansion and contraction, and for movement under earthquake conditions. In addition to the mechanical complexities, the elevated pipeline forms a barrier to cross-traffic. A 48-in. (122-cm) pipeline elevated about 24 in. (61 cm) above the ground forms a very effective fence. Provisions had to be made for passage of both men and animals.

The Vertical Support Members (VSM) System was designed to resist loads either in friction along the sides of the VSM or end bearing at the VSM tip. Five VSM types were used. They were the conventional friction and end bearing piles, and the unconventional adfreeze, thermal, and end bearing thermal.

Most of the support system piling or VSM's were placed in 24-in. (61-cm) holes that were drilled or augured in a manner that provided detailed information on the nature of the *in situ* material being penetrated, and the data thus obtained were used to define the length of the VSM required, the type of backfill, the amount of VSM corrugation or welded protrusions, and the need for thermal heat tubes. The fact that the subsurface data varied from hole-to-hole, and that each VSM design was finalized in the field between the time the hole was drilled and the VSM set, required that extensive field engineering be accomplished on a very tight time schedule.

About 62,000 of the 78,000 VSM's placed in thaw-unstable permafrost had heat transfer devices installed to dissipate more heat from the surrounding ground during winter than is introduced by conduction down the steel pipe during the summer months. The heat pipes consist of sealed sections of pipe containing anhydrous ammonia and topped by a finned radiator. Two heat pipes were installed in each 18-in. (46-cm) VSM (4). The heat pipes are designed to operate when the temperature of the air is colder than the ground temperature. The ammonia absorbs heat from the soil, vaporizes, and rises; the heat is discharged into the air through the radiator. The ammonia vapor then condenses and returns to the bottom of the pipe where the cycle is repeated. During the summer they will remain dormant. In this way, the frozen condition of the permafrost will be maintained year-round.

In the buried line the friction between the buried pipe and normal "bedding"

material holds the pipe in place once located in a ditch. None of these latitudes were available during installation of the pipe aboveground. Any slight variations of the aboveground mode in the straightness of assembled pipe sections, differences between the bends as designed and actually installed, and small length variations, all presented problems when the pipe was placed on the aboveground support system. Therefore, the mainline pipe was secured to clamps which are designed to slide both longitudinally and across horizontal beams supported by at least two VSM. Mainline valves in the aboveground portions of the line also are supported on horizontal platforms to allow similar movement in any direction. There are anchors at the appropriate places, usually at the midpoint of the long trapezoid (zigzag sections) legs, so that normal movement resulting from thermal changes in the pipe is confined to individual zigzag sections. The support system allows no vertical movement. Any vertical adjustment of the system during construction was provided by the use of split rings welded to the VSM to support the horizontal system.

Provisions for free passage of game movements through aboveground sections of the pipeline were required. Consequently, aboveground and specially constructed belowground animal crossings are provided. An aboveground animal crossing requires a minimum clearance of 10 ft from the bottom of the insulated pipe to the top of the workpad over the distance between two intermediate supports, or about 60 ft (18.3 m). Buried animal crossings in aboveground sections were constructed in areas where migrating caribou might avoid overhead pipe or vertical support members. These crossings varied in length from 50 ft–300 ft (15 m–91 m) depending on the evidence of previous use of the area as a migration route.

The aboveground support system is a new type of construction mode for cross-country pipelines in this country. The design and construction ingenuity in this portion of the line are noted. There were few problems in a broad sense with this unconventional construction mode, yet, it was the vehicle to accommodate heretofore serious design problems with the permafrost and seismic concerns.

Buried.—Except for three pipeline segments using special burial techniques, the belowground pipe was located in: (1) Perennially thawed soils; (2) bedrock, whether frozen or thawed; and (3) certain types of perennially frozen (permafrost) ground thaw-stable sands and gravels which will be heated by the warm pipe. The alteration of the thermal regime within these thaw-stable permafrost areas would not directly jeopardize the integrity of the pipeline; however, it causes concern as possible extraordinary source of maintenance problems, such as: (1) The changes in the surface drainage system resulting from construction of the workpad and the buried pipe, plus possible alteration of subsurface water conditions due to the introduction of a thawed and permeable flow path along the right-of-way; and (2) the introduction of heat into those areas where the pipeline is buried in thaw-stable material, but where there is thaw-unstable material either above or adjacent to the pipe spring line, could result in changes to the land surface or unexpected pipe problems.

These concerns were considered during the design and the advantages of direct burial of the pipeline were found to outweigh the problems for approximately 360 miles (579 km) of the line, as follows:

(1) A buried restrained pipeline remains relatively fixed and will not be subject

to severe concentrations from thermal or seismic forces; (2) the earth cover acts as insulation and a heat sink so that once oil flow has warmed the area, only limited heat loss will occur; and (3) buried pipe is out-of-sight and not readily subject to accidental (third party) damage.

Much of the ditch excavation required blasting to loosen rock and frozen material. Most of the actual ditch excavation was by backhoe and clamshell excavators used to reclean the ditch if wall sloughing occurred. Sloughing was particularly a problem where thaw-unstable material was exposed in the upper portion of the ditch walls.

When the ditch was completed, elevation profiles were made to determine the location and angle of bends to be made and the pipe was generally bent by a hydraulic bending machine on the workpad. Pipe field bending was done with no more than 12 degrees of curvature in a 40-ft (12.2-m) joint, leaving 6 ft (1.8 m) of straight tangents on each end of the joints of pipe (22). After bending, the pipe was welded, taped, and stored on skids until it was lowered into the ditch.

In contrast to the aboveground pipe, the hot oil buried line is fully restrained. Special bedding and padding material was used around and over the top of the pipe to provide adequate frictional resistance for the thermal design stresses while simultaneously protecting pipe covering (tape).

Before the pipe was placed in the ditch and after the tie-ins were completed in the ditch, the pipe and tie-in girth welds were taped. Subsequently the cathodic protection anodes, zinc ribbons, were installed on both sides of the pipe prior to backfilling. While the buried line is considered conventional construction (with the exception of being designed as fully restrained), more problems were experienced with the buried portions than with the aboveground mode. This was generally attributed to the unfamiliarity of the contractors with the environment in which they had to work and with the specifications they were to follow. Final backfilling of the ditch was completed using conventional methods.

Special Burial.—At special locations along the pipeline route, it was found necessary to bury the pipe in potentially thaw-unstable permafrost to accommodate avalanche conditions and the free passage of big game animals. One technique, used at three locations totaling approximately 4 miles (6.43 km) of the line, utilizes 6-in. (15.2-cm) chilled coolant (brine) circulation pipes laid in the ditch bedding alongside the insulated pipe (5). The coolant pipes reduce heat transfer and provide heat removal to maintain the soil in a frozen state. The heat removed by the circulating coolant is, in turn, transferred to a refrigerant in the coolant heat exchanger and from the refrigerant to the atmosphere through an air-cooled condenser. These special buried sections have only worked fairly well to date. They are, however, effectively serving their intended purpose for free passage of large game animals. At Atigun Pass, an insulated box was used to control heat flow into thaw-unstable areas while protecting the pipe from potential avalanche by burying the pipe.

Workpad and Pipeline Disturbed Areas.—A workpad was constructed for most of the 800-mile (1,287-km) pipeline route to provide a working platform during summer months and to minimize erosion problems caused by pipeline activities. To prevent thawing of permafrost below the pipeline workpad north of the Brooks Range in Alaska, Alyeska insulated the pad with layers of formed polystyrene "planks" buried in gravel (5). South of the Brooks Range, where

thawing could not be prevented in the long-term even with extremely large amounts of insulation, only conventional measures were employed to allow passage of construction traffic.

Use of the insulation on the northern part of the line substantially cut down on the amount of gravel required to build the pad and the number of sites which had to be disturbed to obtain it. The installation also made it possible to reduce the length of vertical support members installed in the pad to support the 48-in.-diam oil pipeline. Insulation with gravel alone would have been possible in this area but would have required a minimal workpad 5 ft thick. By using insulation, however, Alyeska was able to reduce the gravel overlay to an average, on level ground, of only 24 in. (61 cm), 2 in.–4 in. (5 cm–10 cm) of foam insulation.

In the foothills of the Brooks Range, from 3 in.–4.5 in. (7.6 cm–11.4 cm) of the polystyrene were placed in layers within the workpad. On the rolling tundra north of the Brooks Range, insulation thickness ranged from 3 in.–4 in. (7.6 cm–10 cm) and on the flat coastal plain from 1.5 in.–3 in. (3.8 cm–7.6 cm).

Pipeline disturbed areas were most often similar to, and an extension of, the workpad. The workpad and pipeline disturbed areas were of significant concern environmentally. The designs called for protection and passage of fish and wildlife as well as preservation of the habitat they require for survival. As an example, construction was scheduled so as to minimize interference with critical activities of fish and wildlife, such as fish spawning and bird nesting. Also, the design called for all disturbed areas to be stabilized. Most often this was accomplished through revegetation of the disturbed areas.

The thermally designed workpad is a viable and environmentally sound method of construction.

River Crossings.—The pipeline crosses more than 800 streams and rivers between Prudhoe Bay and Valdez. These range in size from mere trickles to the huge Yukon River, a half-mile (0.8 km) wide at the point of pipeline crossing. At 13 other locations, major bridge structures were selected as the most practical means of crossing because of existing flow characteristics, soil, and environmental considerations.

Conventionally, the most economical method of building a pipeline is to bury it. This usually also applies to major river crossings. Buried major river crossings posed greater environmental damage during construction due to river upset conditions and siltation from excavation and backfilling of the pipe. However, during operations to date, no significant environmental problems have been noted.

Buried river crossing like buried construction caused many problems with major reworking of three such buried crossings necessary (conventional construction). Elevated river crossings posed little, if any, problems (while bridges are conventional they are considered general unconventional construction in the pipeline industry).

Valves (17).—A total of 151 valves, more per mile than on any other line like it in the world, are installed along the pipeline and at the pump stations and terminals. Valves along the line include 62 remotely operated valves, 71 check valves, and nine check and manual block valve combinations. The remote gate valves are provided with continuous power for the radio and supervisory

control through batteries and/or commercial power. The valves automatically shut down the line in case of a break.

Block valves in the system are capable of stopping oil flow from either direction. They would be used to limit drainage in event of a leak or break and to isolate pump stations, the terminal, or any damaged sections of the pipeline so that maintenance could be carried out. Remote block valves are operated by electric power drives. They are required to be operational at −50° F (−46° C).

Check valves, which prevent a reversal of oil flow, are installed on uphill slopes to prevent downhill flow in event of a break. Flow in one direction keeps the valves open. When flow reverses, the valves close automatically.

All valves are designed for 1,200-psi (8,274-kN/m^2) working pressure.

In designing the valve system, every section of the pipeline was analyzed as to risk and resource values. The risk of failure, as indicated, is very remote. But, still, these risks were assessed for every mile of the line. And where risks could be high or where resource values such as wildlife, fish, and recreation were higher than elsewhere, valve systems were installed to limit the size of any possible spill.

Spills on the average section would be limited to 13,000 barrels (2,067 m^3) after valves were closed. Maximum static spills after valves are closed would be held to 50,000 bbl (8,000 m^3) and these in only a few unusual terrain situations on less than one-half of 1% of the line.

Fault Crossings.—The pipeline crosses three active faults. They are: Denali, McGinnis Glacier, and Donnelly Dome. The pipeline crosses these faults in the elevated mode. At the Denali Fault, special long-width support beams are installed on gravel berms to permit a fault displacement of 20 ft (61 m) horizontally and 5 ft (1.5 m) vertically. At Denali Fault, valves would limit static spills to 5,000 bbl of oil.

Pump Stations (3).—A total of 12 pump stations at full design throughput of 2.0 million barrels (320,000 m^3) will move the crude oil between Prudhoe Bay and Valdez. Each station will have three multistage centrifugal pumps driven by 13,500-hp jet engine power turbine drivers.

Small refineries or topping units produce a turbine fuel specifically designed for jet engines at Pump Stations 6, 8, and 10 to supply fuel for the other stations south of the Brooks Range.

Also included at Pump Stations 1, 5, and 10, and at the terminal, are facilities for launching or receiving cleaning and monitoring scrapers from within the pipe. Each station has high pressure block valves installed in the oil stream. One set of valves, located at entry and exit boundaries, will block the main flow providing operators with the means to isolate the station in an emergency. A second set may be used to block the line while allowing incoming oil access to the relief tanks. A third set allows oil to flow through the main line without passing through the station pumps and provides the means for scrapers to pass through the line, bypassing the pumps.

Each station is equipped with an automatic pressure relief system. When excess static and surge pressures are detected in the pipeline, relief valves will divert oil out of the line into a 55,000-bbl (8.745-m^3) pressure relief tank. When normal operating conditions are restored, a booster pump will transfer oil from the relief tank back into the line.

Most of the stations are built on relatively stable grounds; however, at Pump

Stations 1, 2, 3, 5, and 6, some structures are built on refrigerated foundations. Coils of pipe to circulate cold brine are buried in gravel beneath plastic foam insulation mats underneath structures to keep the permafrost stable.

Although the pump stations are similar to those presently in operation on other pipelines, the Alyeska stations are specifically designed to meet the challenges of the severe Alaska environment. All of the equipment and virtually all of the station piping is being housed in insulated, windowless buildings connected with covered hallways.

The stations are operated by remote control from the Valdez Terminal. Operating crews remain at each station to provide needed maintenance and surveillance of equipment.

Terminal (17).—The Trans-Alaska Pipeline Marine Terminal is situated on approximately 1,000 acres (404 ha) on the south shore of Port Valdez which is a natural ice-free port. Some of the more interesting design considerations included accommodating 100-psf snow loads, 100-mph winds, −20° F–+80° F (−27° C–+27° C) temperature differentials, and seismic forces equivalent to an 8.5 Richter magnitude earthquake.

Oil arriving at Valdez is stored in tanks until it is loaded aboard tankers for shipping to West Coast ports. The facility represents an investment of 1.3 billion dollars and 3 yr of continuous construction effort to build the terminal. The complex contains such facilities as the following.

1. A sophisticated, computerized operations control center which is known as the Operations Control Center. TAPS is controlled remotely from Valdez even though operators exist at all the operational pump stations.
2. Eighteen crude oil storage tanks with a capacity of 510,000 bbl (81,000 m^3) apiece. These welded steel cone-roof storage tanks are each 250 ft (76 m) in diameter and 6 ft (18.9 m) high. The tanks are sited in pairs within containment dikes with capacity equal to 110% of the total volume of the two tanks plus an additional 2-ft (0.6-m) allowance for surface water which may be impounded within the area.
3. Four tanker berths, which will permit simultaneous loading of four tankers, have been built. Three of the docks are fixed to the shore. One is a floating dock.
4. The berths are designed to accommodate tankers up to 250,000 tons (225,000 MT). The ships can be loaded (usually by gravity flow) at the rate of 80,000 bbl–110,000 bbl (12,720 m^3–17,490 m^3) an hour.

Fixed-dock facilities include an operating platform, independent berthing structures, and mooring dolphins. The steel loading arms and storage areas on the loading platforms of both fixed and floating docks are surrounded by an oil-tight curb so that any spillage can be collected and processed through the ballast treatment unit.

Quick release mooring hooks are being provided for ship mooring lines on all docks. The hooks can be released either at the dock or by remote control from the dock operator's building. Shutoff valves on each loading arm can be closed in 2 min either at the dock, from the Operations Control Center, or from emergency shutdown stations also on the docks. Steel articulated loading arms are also equipped with quick disconnect couplings.

An emergency shutoff valve, which can be closed in 30 sec, exists onshore next to each berth. These may also be operated either from the control room or locally. Other valves can be closed at each tank and manifold point.

Also included in the complex are the following.

1. A central water pumping system, using sea water from Port Valdez, supplies water under pressure for fighting fires within the terminal.
2. Numerous safety features to protect the environment and site facilities.
3. A 37.5-MW power generation facility was built to generally power the environmental features of the vapor recovery and ballast water treatment system.
4. Reinforced earthen dikes.
5. Oil vapors, displaced or evaporated from the storage tank complex, which are prevented from escaping into the atmosphere by a vapor recovery system. Inert flue gases from the boilers of the terminal power plant are scrubbed and compressed for discharge into the space above the oil in the storage tanks. This provides an inert gas blanket over the crude oil. The inert gas is to be discharged, under low pressure, into the tanks as oil is being withdrawn for loading. When the storage tanks are being filled, vented gas is withdrawn to the vapor recovery unit for reprocessing. Any excess will be bypassed to an incinerator and burned.
6. A ballast treatment facility: Tankers arriving at Valdez will be carrying sea water ballast in their holds. The ballast is taken aboard in order to stabilize the ships while they are traveling without a cargo of oil.

To protect the quality of water in Port Valdez, all oily ballast is pumped from tankers into onshore storage tanks preparatory to processing in a ballast treatment facility. No ballast will be pumped directly into the Sound. The ballast treatment facility is able to accommodate and treat, within 48 h, the anticipated ballast from arriving tankers.

Three tanks provide storage for ballast waste. The 430,000-bbl (68,370-m^3) cone-roofed tanks are made of steel and surrounded by containment dikes.

After being pumped from a ship, the ballast is permitted to settle for a minimum of 6 h in the tanks. Oil which rises during that time is skimmed and pumped to the oil recovery section of the treatment plant and back to the terminal's crude storage tanks. This facility is not only environmentally sound, it more than pays for itself through recovered crude oil which otherwise would be dumped at sea.

The remaining water is passed through a chemically aided, dissolved air flotation treatment unit until it can be discharged at less than eight parts of oil per million, on the average. The cleansed water is dispersed from holding ponds through jet orifices into the sea at a point about 300 ft (91.5 m) below sea level.

Special Operating Features.—Some of the more noteworthy operational features being utilized to control and monitor the operation and environmental concerns of the project are the following.

1. Forward Looking Infrared Radar (FLIR): A unique system was developed to measure, record, and analyze the temperatures of nearly 120,000 heat pipes installed for the pipeline's aboveground sections thus providing an indication

of their effectiveness. Traveling at 40 mph (64 km/hr), 100 ft (30 m) above the pipeline, the FLIR system (carried aboard a helicopter) acts as an aerial thermometer, the results of which are displayed as infrared images on a television monitor.

2. Cathodic Protection: In addition to wrapping all buried sections of the pipeline with special protective tape, sacrificial zinc-ribbon anodes are buried on either side to prevent electrochemical corrosion. If the tape is accidentally pierced during pipe installation, the anode will assure continuous cathodic protection.

The system, designed for the 30-year life of the pipeline, is supposed to operate even if a ribbon should be broken between connection points. Connections at both ends of a section would have to be interrupted to put the section out of service, and such interruptions would be detected in routine checks.

As well as the passive zinc anode system for the protection of the buried pipeline, Alyeska utilizes active, impressed current systems to protect buried piping at pump stations and at the terminal. Storage tank bottoms and tanker berths are similarly protected.

The industry has limited experience with cathodic protection in the Arctic. Therefore, the criteria for protection is not well established and the task of monitoring Arctic pipeline corrosion is more complex. It is too early to determine whether the corrosion control systems that have been implemented will provide satisfactory long-term protection.

3. Communication System: A network of 41 microwave stations between Prudhoe Bay and Valdez serves as the backbone of a four-level communication system which has been developed for control and operation of the Trans-Alaska Pipeline. Other networks include a satellite backup system, remote valves which are controlled by a radio system, and a mobile radio network.

This communication system is unique to the pipeline industry but has experienced no significant problems to date. It has demonstrated that a highly reliable communication system can be provided in a remote Arctic environment without significant problems.

Microwave backbone facilities have been installed generally along the pipeline route in a series of line-of-sight stations located 1.5 miles–40 miles (2.4 km–64 km) apart. Three master control stations have been built at Prudhoe Bay, Fairbanks, and Valdez. End terminals are installed at Valdez and Pump Station 1. The system also includes 30 intermediate relay stations and spur links to eight pump stations.

The geostationary satellite, Satcom II, in orbit approximately 25,000 miles (40,250 km) above the equator handles data required for pipeline operations in the event of any communication loss on the chain of microwave stations.

4. Leak Detection: For the protection of the Alaskan environment during operation of the Trans-Alaska Pipeline, Alyeska is required to provide for oil spill control. Oil spill control is defined as the detection, location, containment, and cleanup of oil spills. In part, Alyeska has provided for these requirements in the design of the Pipeline Supervisory Control System (PCS).

The PCS is comprised of various subsystems, which include a communications network, various controls (both manual and automatic) for the regulation of flow rates and pressure, a special valve network for the containment of oil, an instrumented Leak Detection System, and an Earthquake Monitoring System.

The visual surveillance program, both ground and aerial, forms an important part of the overall leak detection capability.

There are four instrumented leak detection methods (Pressure Deviation, Line Volume Balance, Flow Deviation, and Flow Balance).

Conclusions

Industry has completed, and is operating, the largest free enterprise privately financed project ever undertaken in this country. The Trans-Alaska Pipeline thus began a new chapter in the story of large resource development projects in this country. As we approach the Twenty-First Century, it is expected many more such projects (such as oil-shale development) will be forthcoming.

TAPS was accomplished on schedule in accordance with a two-pronged Congressional mandate: To make this country less dependent on foreign sources of oil, and to execute the project in an environmentally sound manner. The Government issued a set of regulations that industry agreed to follow. These regulations provided for Governmental oversight of industry's design and construction efforts. It should also be remembered that often the designers had to make decisions as to various component features before approval by the Government in order to allow sufficient lead time for manufacturing and delivery. The project is well designed, constructed, and operated. While the project has had its upset conditions, both in construction and operation, those conditions, although unfortunate, are minor when considered in light of the overall project scope and complexity.

TAPS is a monument to the integrity of the designers, builders, and operators of the project. Some of the more important concepts and considerations used to protect the environment are:

1. Project siting is an extremely important consideration. Environmental protection can best be ensured by early Government and industry participation in the route and facility location selection process.
2. Litigation should not preclude project design decisions. If the project is *not* authorized, nothing is lost. If it *is* authorized and decisions have been postponed, the environment and public suffer the consequences.
3. Industry and Government need to understand and address environmental concerns through their own research programs accomplished prior to construction.
4. A need exists for faster decisions on such capital intensive and energy-related projects. For example, cost escalations were caused by the oil embargo by the Organization of Petroleum Exporting Countries (OPEC) in 1974–1975. It can be speculated that if the TAPS had been operational in 1974, which was possible, inflation would be far less today.
5. A need exists to better understand the climate in which we must work and in which the product must function in order to fully address the total environmental consequences of which man is a most important part.
6. Engineering performance was up to design challenges of this project. Many innovative designs and state of the art features were developed.
7. Ice bridges, snow pads, and winter construction, if properly constructed and scheduled, can and should be used in selected areas to minimize environmental impact.

8. Conventional construction methods in northern latitudes posed more real problems than did unconventional construction methods.

9. In some cases, industry and Government regulations need to be revised to appropriately apply to the area of application through the use of recent technological developments.

10. The unconventional design methods have been environmentally superior to conventional construction methods in the Arctic.

11. Overconservation in geotechnical engineering (14) can easily add millions of dollars to such a project. While safety should not be compromised, overconservation can defeat its purpose and lead to wasteful and less satisfactory solutions than if reasonable risks were accepted.

12. Use of insulation in the Haul Road, workpad, and pipeline has advanced the state of the art considerably.

13. Elevated support systems on the pipeline are among the most competent designed systems existing today. The VSM design alone represents thousands of man-hours of field investigation, design, field evaluation of subsurface conditions as the holes were being drilled, and decision on the type of piling to be used.

14. The Yukon-Prudhoe Haul Road has the potential for the biggest environmental problems because it provides the vehicle for people to use the land.

15. TAPS has demonstrated that large resource development projects can be accomplished in an environmentally sound way (16).

Acknowledgments

The writer would like to express his appreciation to all those who have contributed to design, construction, and operation of the Trans-Alaska Pipeline Project. The views presented herein are those of the writer and do not represent an official statement of the Department of the Interior.

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DISCUSSION

Note.—This paper is part of the Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. TE3, May, 1981. ISSN 0569-7891/81/0003-0383/$01.00.

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SULFUR: POTENTIAL PAVEMENT BINDER OF THE FUTURE[a]

Closure by Gerald D. Love,[5] F. ASCE

In this discussion of the paper by Ray, exception was taken to the statement that portland cement concrete can be a substitute for asphalt only in new pavement construction. The writer concurs that there are exceptions to this statement as Ray has pointed out. However, in general practice, portland cement concrete is not utilized to any significant degree as a substitute for asphaltic concrete for the maintenance, resurfacing, rehabilitation and reconstruction of existing flexible pavements.

Ray has also cited examples where portland cement concrete has been utilized for the economical construction of lower type pavements. Again, these projects are exceptions to the general practice as evidenced by the fact that approx 93% of the total mileage of surfaced highways and streets in this country have some type of asphalt surface.

The purpose of noting current pavement construction practices in the United States in the paper was to highlight the fact that the highway industry is highly dependent on the continuing availability of asphalt cement, a petroleum based product, for the economical maintenance and reconstruction of the nation's existing highway system. The research leading to the development of plasticized sulfur as a viable flexible pavement binder was undertaken because of the many uncertainties associated with the possible future supply of petroleum based products.

This concern has been reinforced by events that have occurred since the paper was prepared in 1978, as reflected by the escalation in the price of imported crude oil from $2.00/barrel in early 1973 to the current OPEC maximum price of $41.00/barrel.

The future use of Sulphlex as a widely accepted alternate pavement binder material will be primarily dependent upon:

1. A sufficiently funded and effective research and development program targeted at the optimization of the engineering properties of the Sulphlex binders for use in pavement construction.
2. Supportable evidence of the adequate serviceability of experimental Sulphlex pavements. A total of five Sulphlex experimental projects are now in service in the states of Texas, North Dakota, Nebraska, Pennsylvania, and Florida.
3. The commercial production of Sulphlex in sufficient quantity and at an economically acceptable price.
4. A continuation of the current trend in the rapid escalation of crude oil prices and the tenuous nature of foreign crude oil supplies.

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[a]September, 1979, by Gerald D. Love (Proc. Paper 14835).

[5]Assoc. Administrator for Research and Development, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C. 20590.

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3. Generally, the maximum length of a paper is 10,000 word-equivalents. As an *approximation*, each full manuscript page of text, tables or figures is the equivalent of 300 words. If a particular subject cannot be adequately presented within the 10,000-word limit, the paper should be accompanied by a rationale for the overlength. This will permit rapid review and approval by the Division or Council Publications and Executive Committees and the Society's Committee on Publications. Valuable contributions to the Society's publications are not intended to be discouraged by this procedure.

4. The author's full name, Society membership grade, and a footnote stating present employment must appear on the first page of the paper. Authors need not be Society members.

5. All mathematics must be typewritten and special symbols must be identified properly. The letter symbols used should be defined where they first appear, in figures, tables, or text, and arranged alphabetically in an appendix at the end of the paper titled Appendix.—Notation.

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9. References cited in text should be arranged in alphabetical order in an appendix at the end of the paper, or preceding the Appendix.—Notation, as an Appendix.—References.

10. A list of key words and an information retrieval abstract of 175 words should be provided with each paper.

11. A summary of approximately 40 words must accompany the paper.

12. A set of conclusions must end the paper.

13. Dual units, i.e., U.S. Customary followed by SI (International System) units in parentheses, should be used throughout the paper.

14. A practical applications section should be included also, if appropriate.